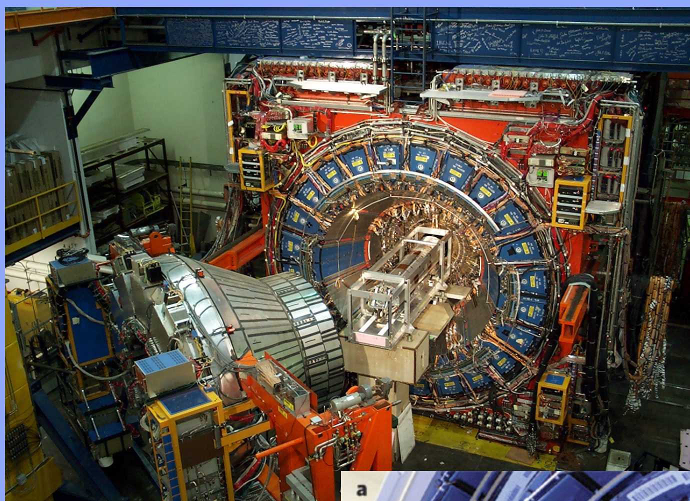
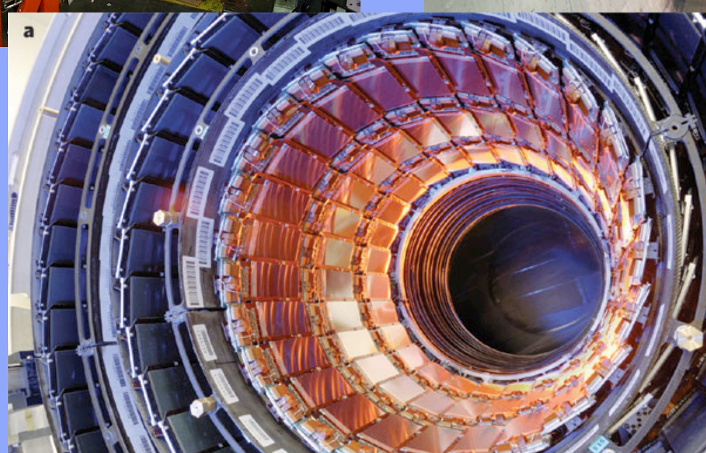
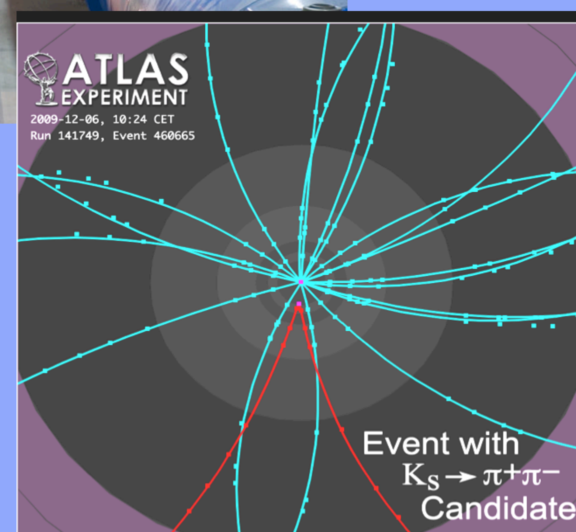
Particle Physics from Tevatron to LHC: what we know and what we hope to discover







Beate Heinemann, UC Berkeley and LBNL

Università di Pisa, February 2010

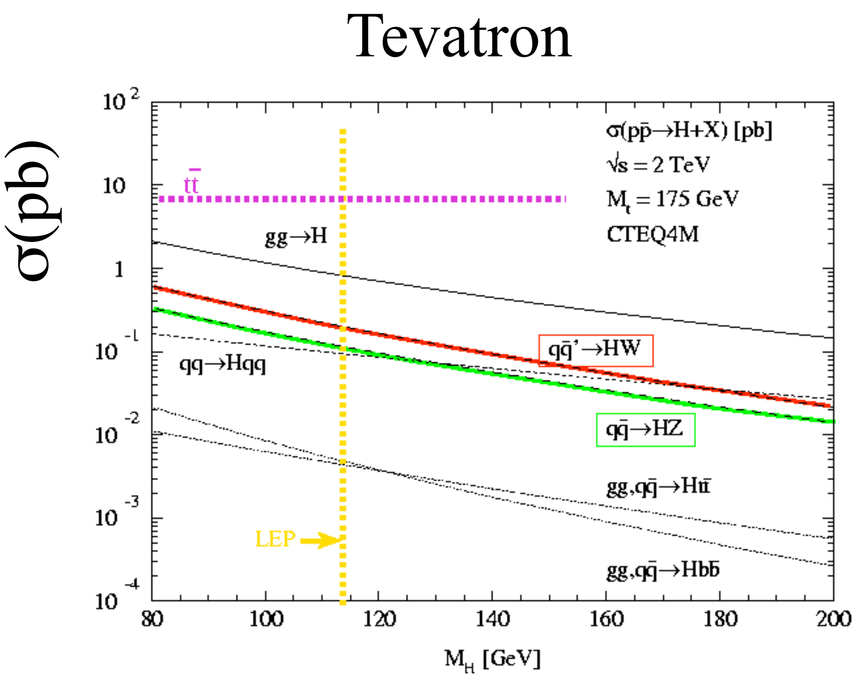
Outline

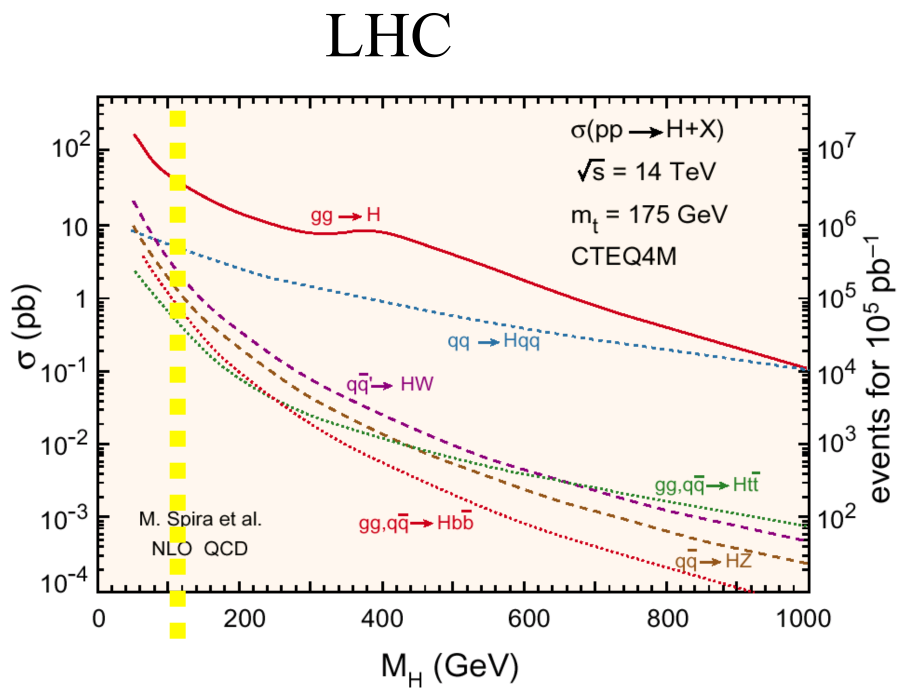
- **Introduction**
  - Outstanding problems in particle physics
    - and the role of hadron colliders
  - Current and near future colliders: Tevatron and LHC
- **Standard Model Measurements**
  - Hadron-hadron collisions
  - Cross Section Measurements of jets, W/Z bosons and top quarks
- **Constraints on and Searches for the Higgs Boson**
  - W boson and Top quark mass measurements
  - Standard Model Higgs Boson
- **Searches for New Physics**
  - Higgs Bosons (beyond the Standard Model)
  - Supersymmetry
  - High Mass Resonances (Extra Dimensions etc.)
- **First Results from the 2009 LHC run**

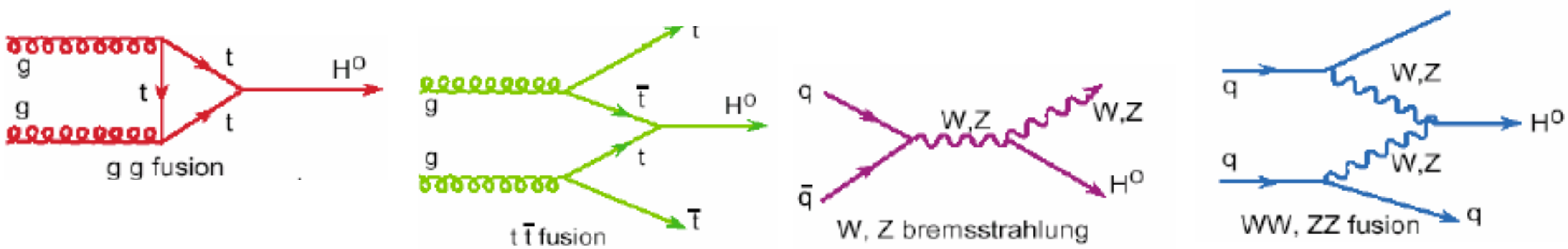
Low Mass: m_H<140 GeV

- Tevatron:
  - $WH(\rightarrow bb)$, $ZH(\rightarrow bb)$
- LHC:
  - $H(\rightarrow \gamma\gamma)$, $qqH(\rightarrow \tau\tau/WW^*)$

Higgs Production: Tevatron and LHC



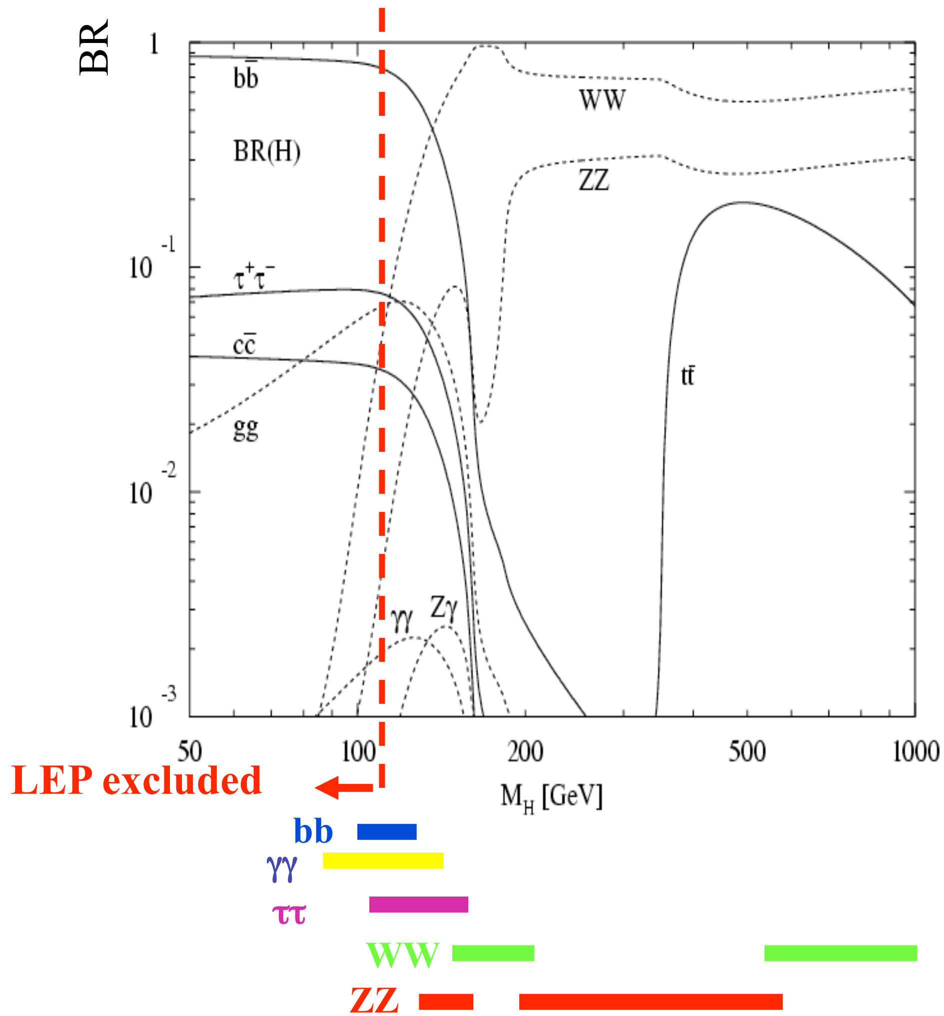




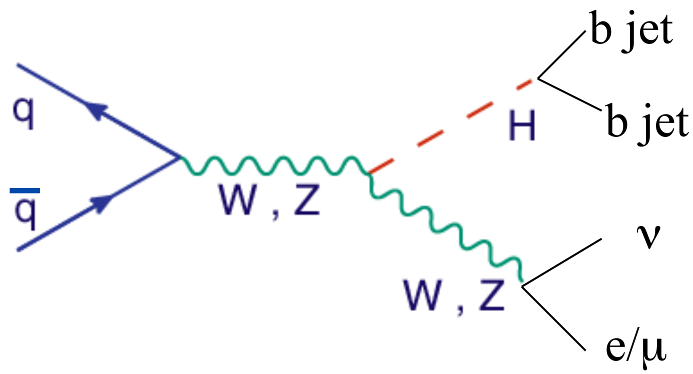
dominant: gg→ H, subdominant: HW, HZ, Hqq

Higgs Boson Decay

- Depends on Mass
- M_H<130 GeV/c^2:
  - $b\bar{b}$ dominant
  - WW and $\tau\tau$ subdominant
  - $\gamma\gamma$ small but useful
- M_H>130 GeV/c^2:
  - WW dominant
  - ZZ cleanest

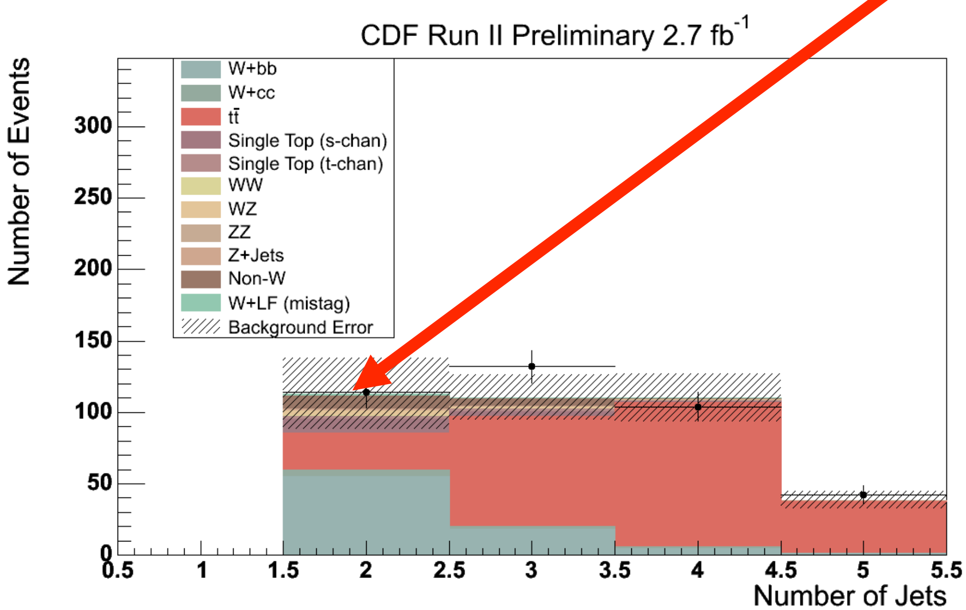


WH→lνbb



- **WH selection:**
  - **1 or 2 tagged b-jets**
  - **electron or muon with p_T > 20 GeV**
  - **E_T^{miss} > 20 GeV**

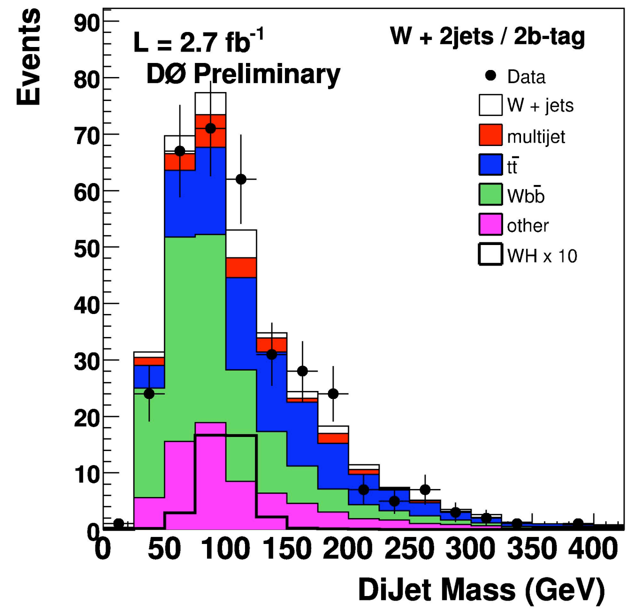
Looking for 2 jets

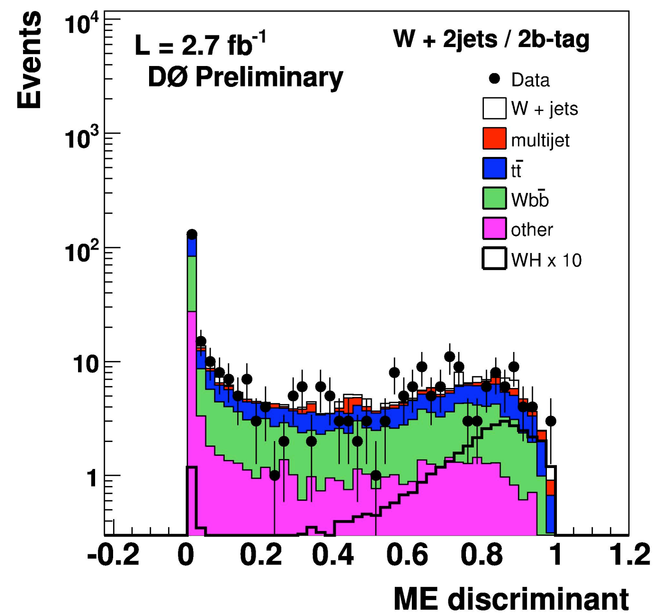


Expected Numbers of Events for 2 b-tags:
WH signal: 1.6
Background: 110±25

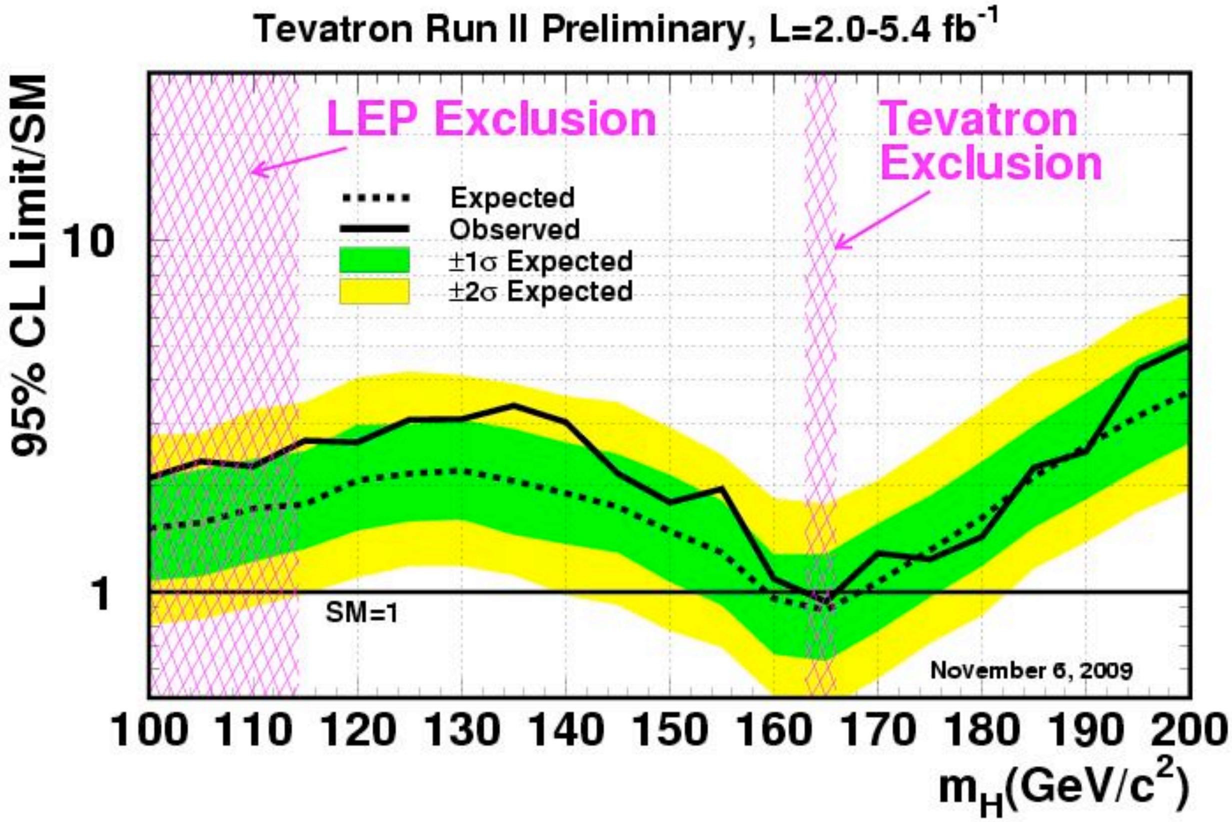
WH Dijet Mass distributions

- Use discriminant to separate signal from backgrounds:
  - Invariant mass of the two b-jets
    - Signal peaks at m(bb)=m_H
    - Background has smooth distribution
  - More complex:
    - Neural network or other advanced techniques
- Backgrounds still much larger than the signal:
  - Further experimental improvements and luminosity required
  - E.g. b-tagging efficiency (40->60%), *NN/ME selection*, higher lepton acceptance
- Similar analyses for ZH





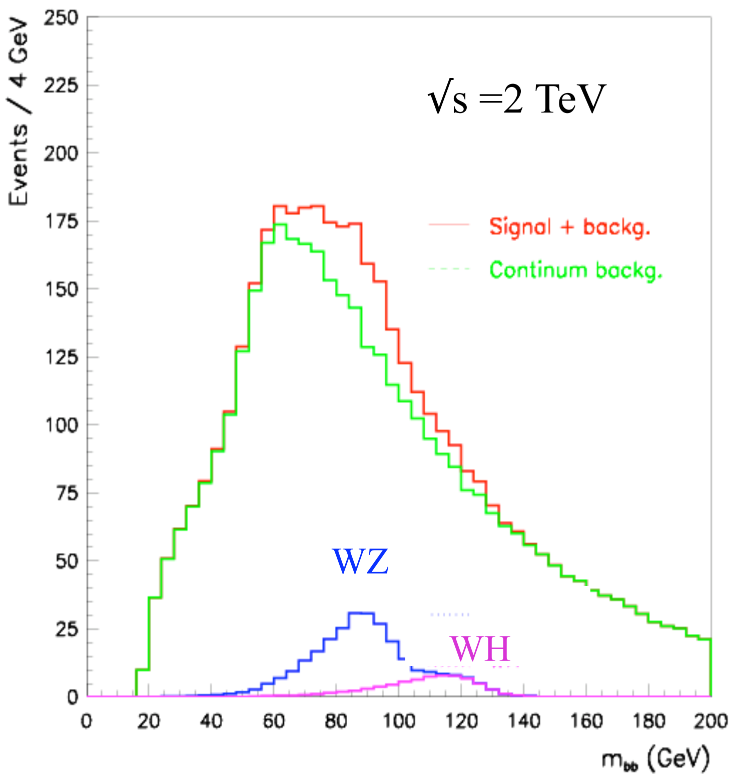
Tevatron Combined Status

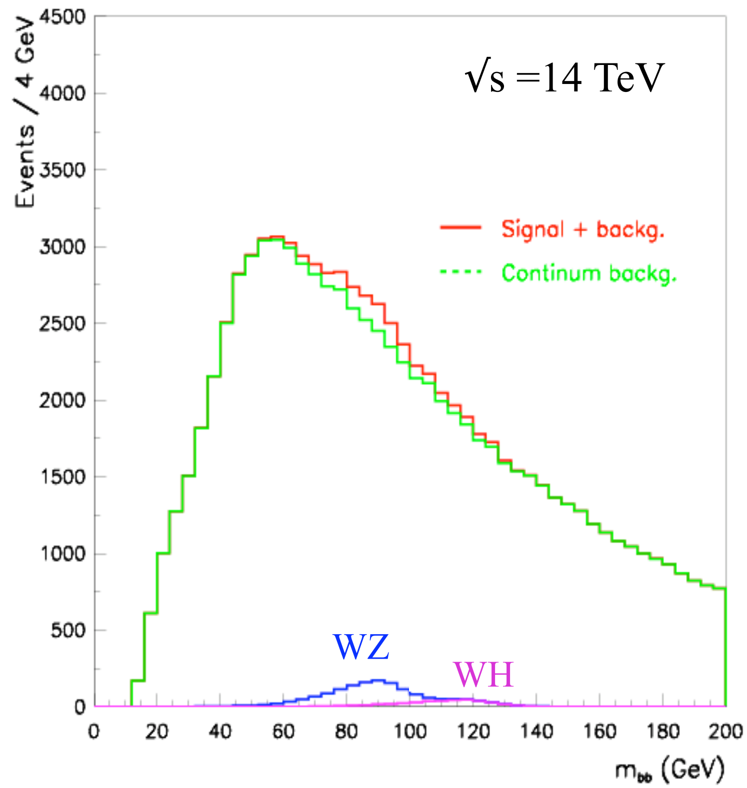


- Combine CDF and DØ analyses from all channels at low and high mass
  - Exclude m_H=163-166 GeV/c^2 at 95% C.L.
  - m_H=120 GeV/c^2: limit/SM=2.8

Higgs at Low Mass: Tevatron vs LHC

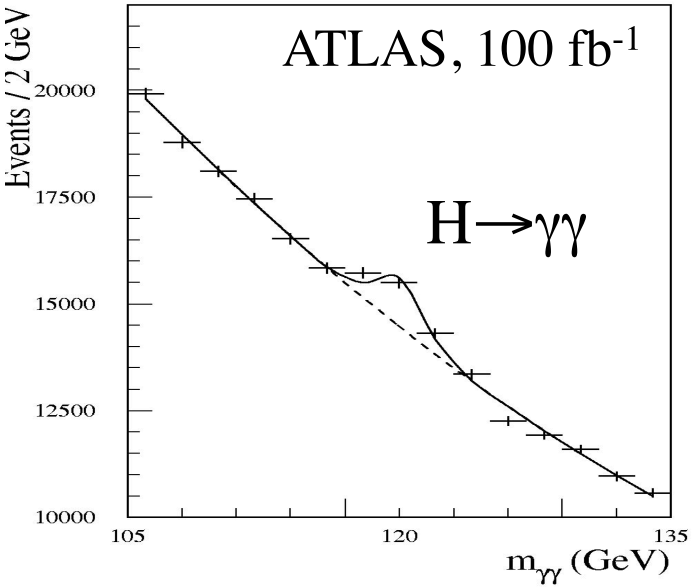
$M_H = 120$ GeV, 30 fb^{-1}

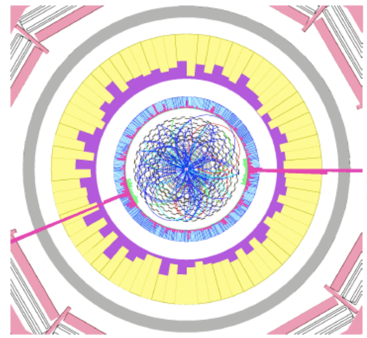


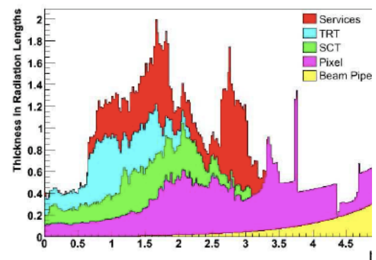


- WH channel:
  - Much larger backgrounds at LHC than at Tevatron
  - Not the best channel at the LHC! => use other ones

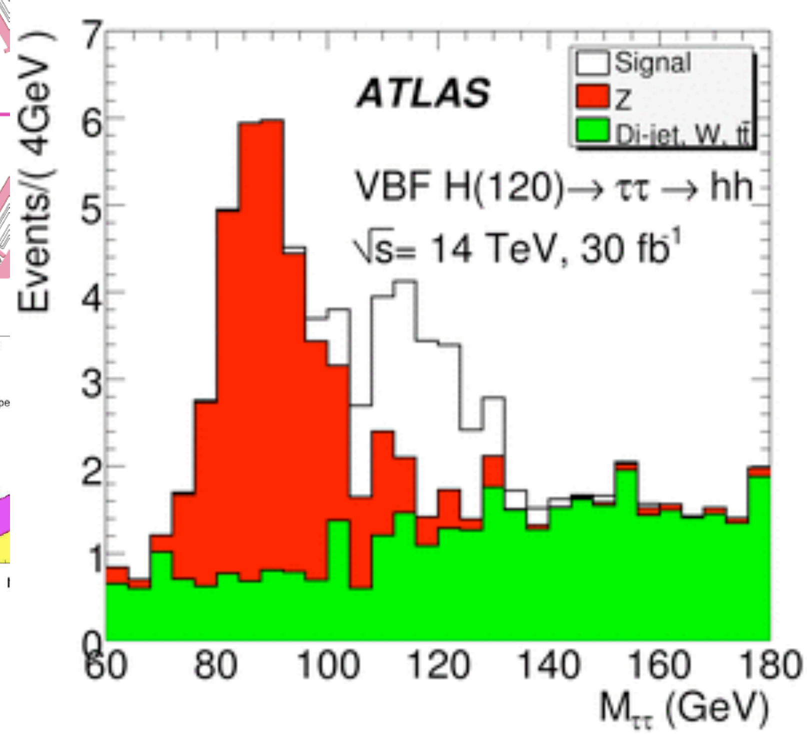
Low Mass Higgs Signals at LHC





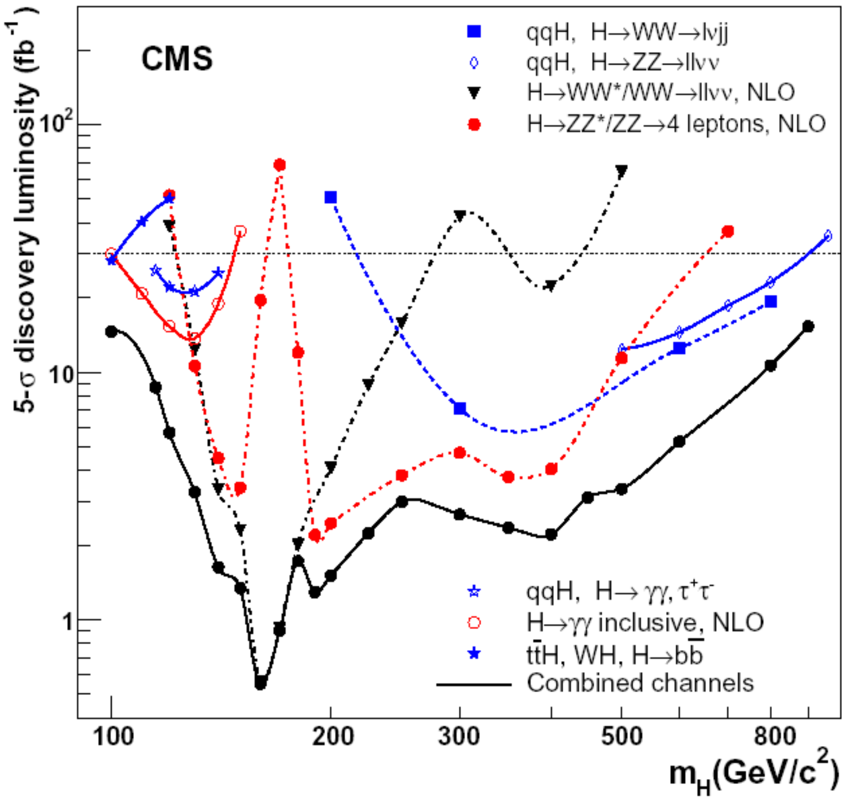


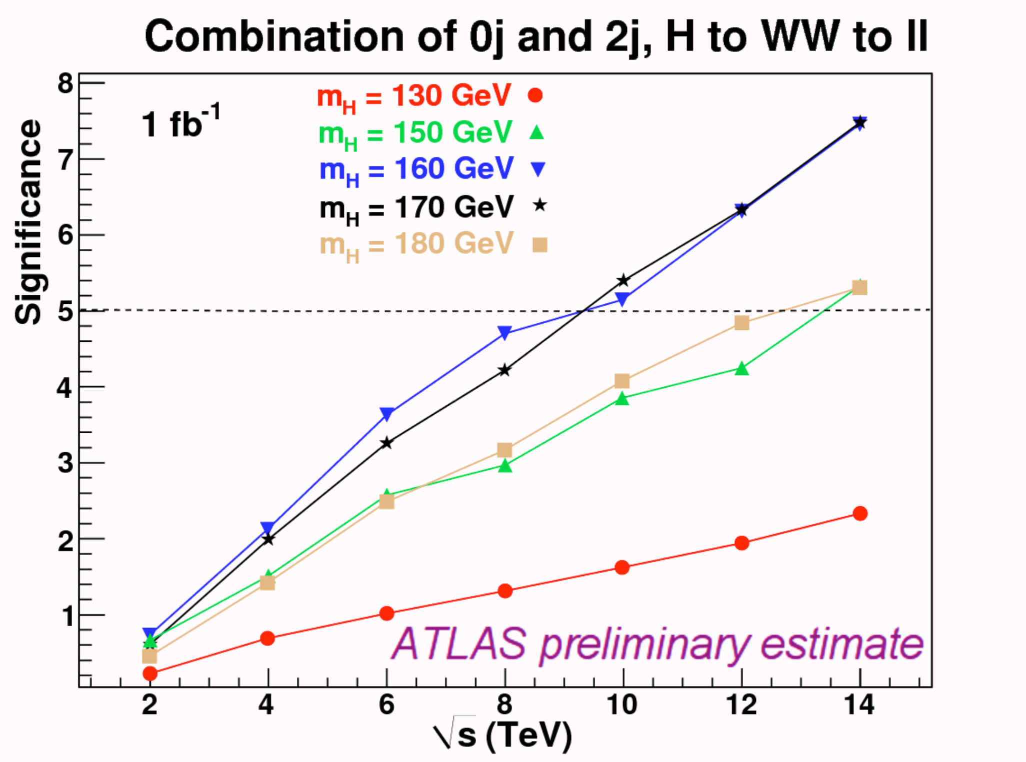
VBF $H\rightarrow\tau\tau$



- Main observation channels:
  - $H\rightarrow\gamma\gamma$
  - $qqH\rightarrow qq\tau\tau$
  - $H\rightarrow ZZ^*$ (only for M>125 GeV/c^2)
- Require at least 10 fb^{-1} of luminosity (2013/2014 ?)

LHC SM Higgs Discovery Potential



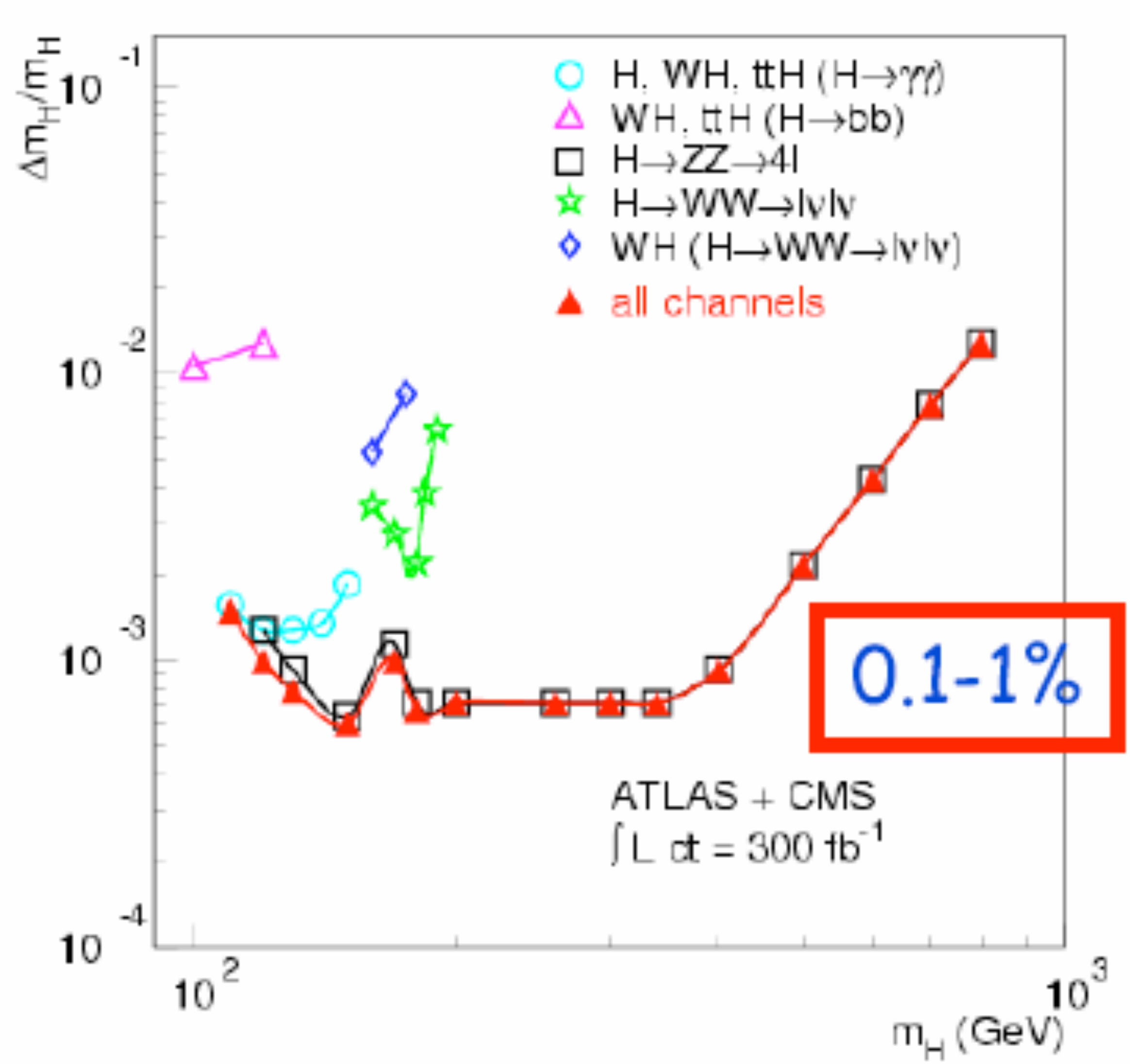


- Sensitivity best at m_H=160 GeV/c^2:
  - Observation possible with ~1 fb^{-1} (or improvement of Tevatron limits)
- Much more difficult at low mass (preferred region)
  - Need at least 10 fb^{-1} to cover full mass range

How do we know what we have found?

- After discovery we need to check it really is the Higgs boson
- Measure it's properties:
  - The mass
  - The spin (very difficult…)
  - The branching ratio into all fermions
    - Verify coupling to mass
  - The total width (very difficult…)
    - Are there invisible decays?
- Check they are consistent with Higgs boson

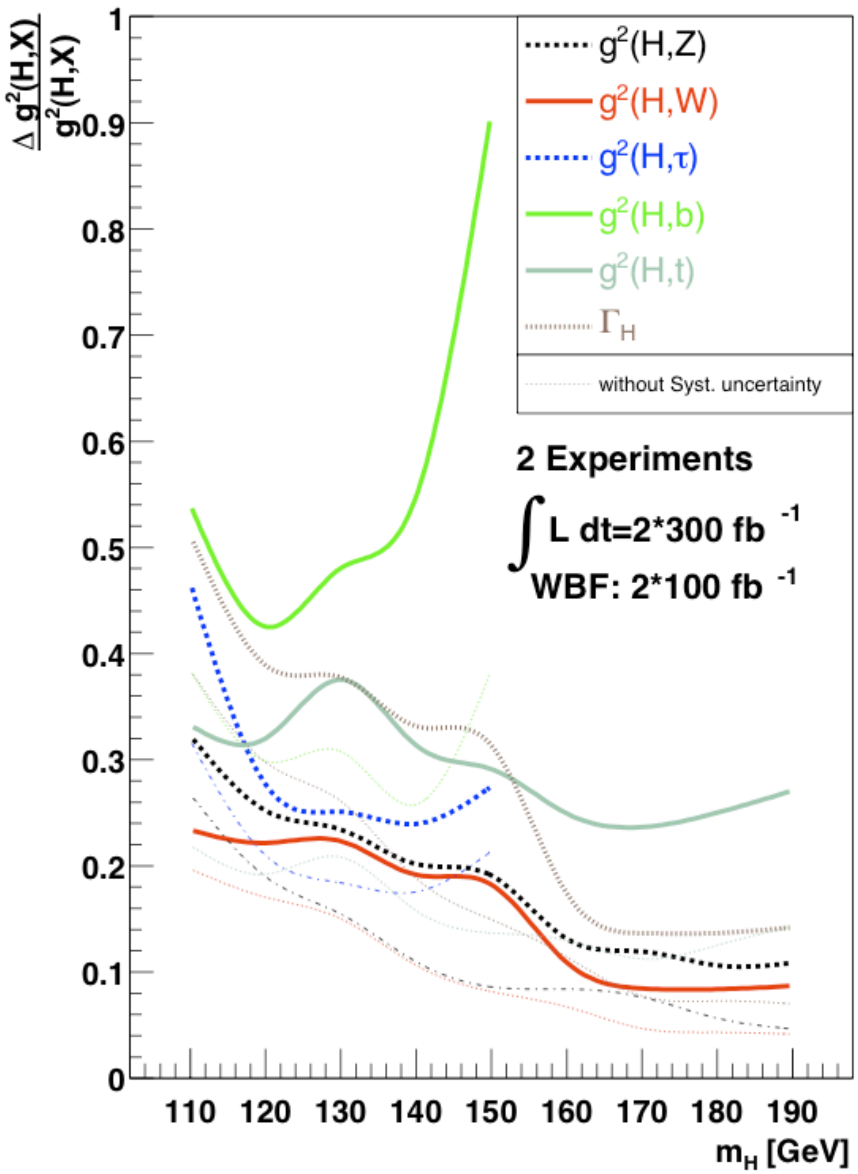
Mass



$\Delta m_H/m_H$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
H, WH, ttH (H→γγ)
WH, ttH (H→bb)
H→ZZ→4l
H→WW→lνlν
WH (H→WW→lνlν)
all channels
0.1-1%
ATLAS + CMS
∫L dt = 300 fb^{-1}
10^2
10^3
m_H (GeV)

Coupling Measurements at LHC

Duehrssen et al hep-ph/0407190

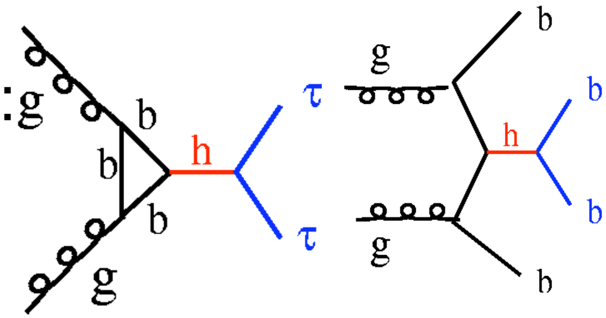


- Measure couplings of Higgs to as many particles as possible
  - $H \rightarrow ZZ$
  - $H \rightarrow WW$
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow bb$
  - $H \rightarrow \tau\tau$
- And in different production modes:
  - $gg \rightarrow H$ (tH coupling)
  - $WW \rightarrow H$ (WH coupling)
- Verifies that Higgs boson couples to mass

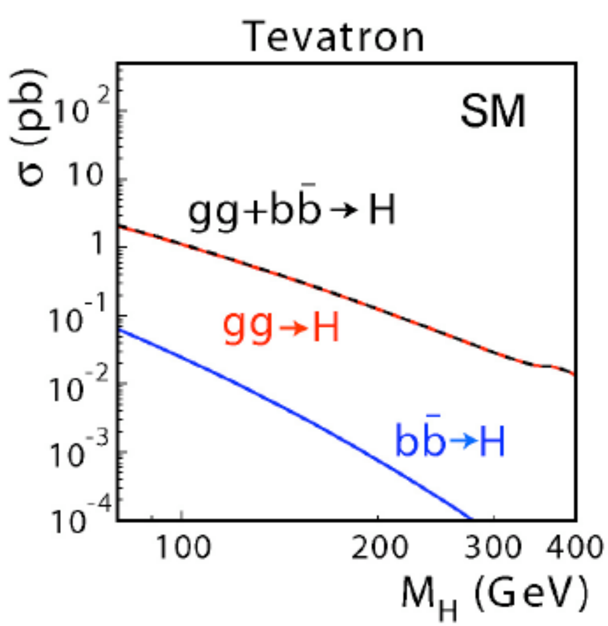
Non Standard-Model Higgs Bosons

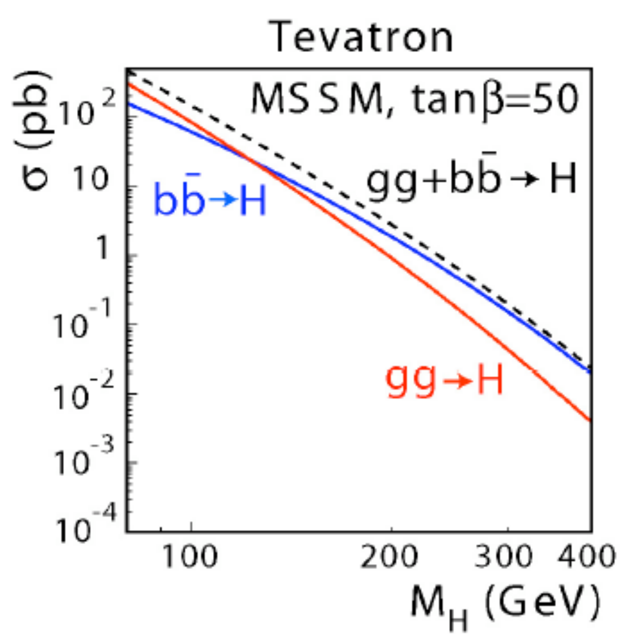
Higgs in Supersymmetry (MSSM)

- Minimal Supersymmetric Standard Model:
  - 2 Higgs-Fields: Parameter $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$
  - 5 Higgs bosons: h, H, A, $H^{\pm}$
- Neutral Higgs Boson:
  - Pseudoscalar A
  - Scalar H, h
    - Lightest Higgs (h) very similar to SM



$$\sigma \times \boldsymbol{BR}_{SUSY} = 2 \times \sigma_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2} \times \frac{9}{[9 + (1+\Delta_b)^2]}$$

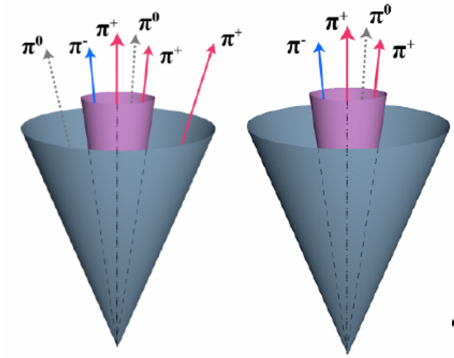


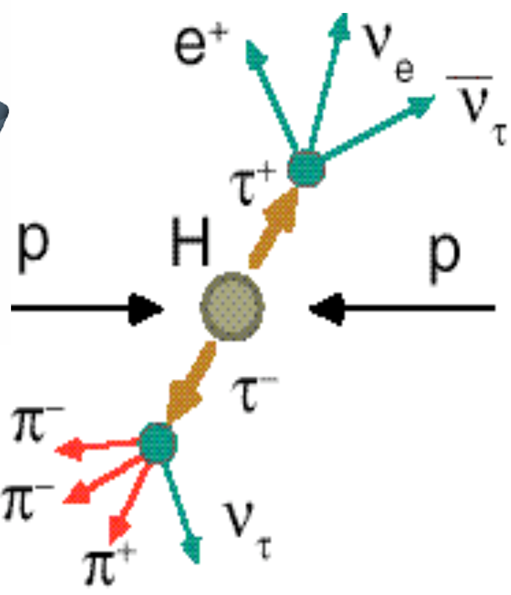


C. Balazs, J.L. Diaz-Cruz, H.J.He, T.Tait and C.P. Yuan, PRD 59, 055016 (1999)

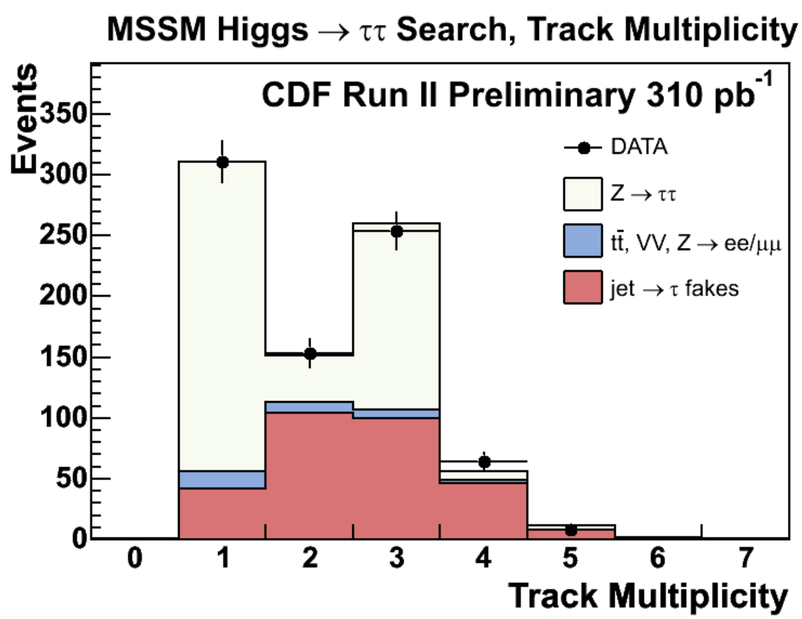
MSSM Higgs Selection

Φ =h/H/A



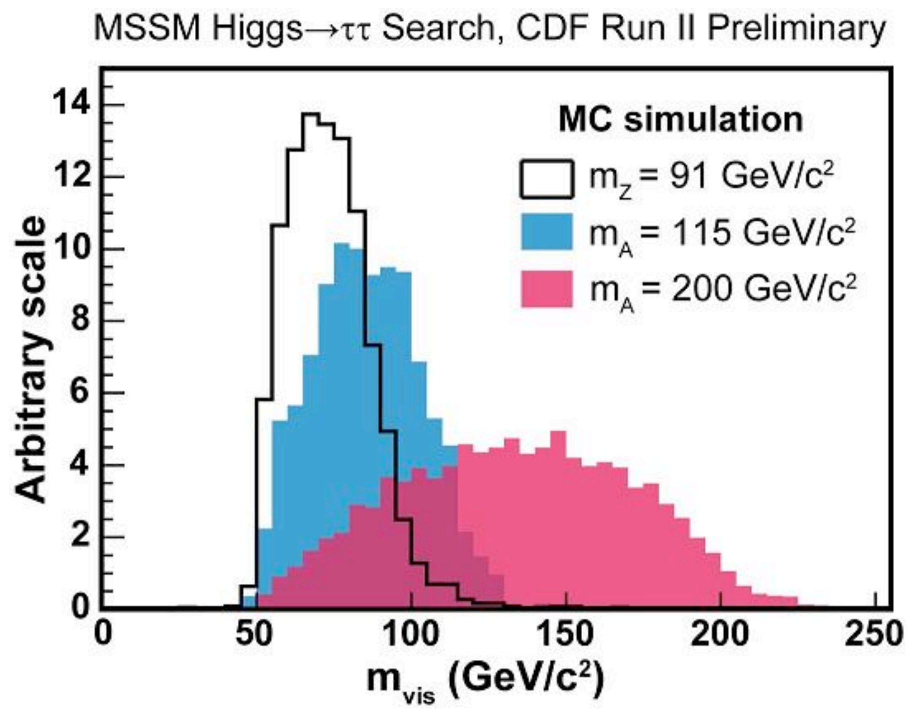


- pp $\rightarrow$ Φ+X $\rightarrow$ $\tau\tau$ +X :
  - One τ decays to e or μ
  - One τ decays to hadrons or e/μ
  - They should be isolated
  - Efficiency: ~50%
  - Fake rate ~0.1-1%
    - 10-100 times larger than for muons/ electrons

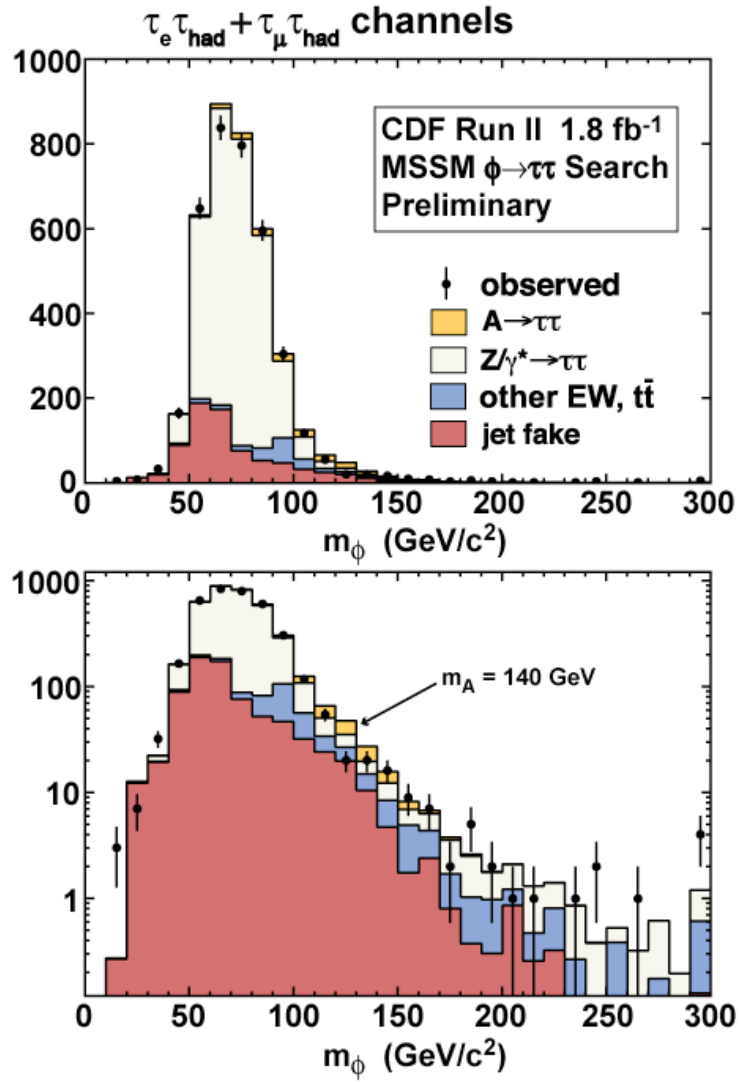


Di-tau Mass reconstruction

- Neutrinos from tau-decay escape:
  - No full mass reconstruction possible
- Use "visible mass":
  - Form mass like quantity: $m_{vis}=m(\tau,e/\mu,\cancel{E}_T)$
  - Good separation between signal and background
- Full mass reconstruction possible in boosted system, i.e. if $p_T(\tau, \tau)$>20 GeV:
  - Loose 90% of data statistics though!
  - Best is to use both methods in the future

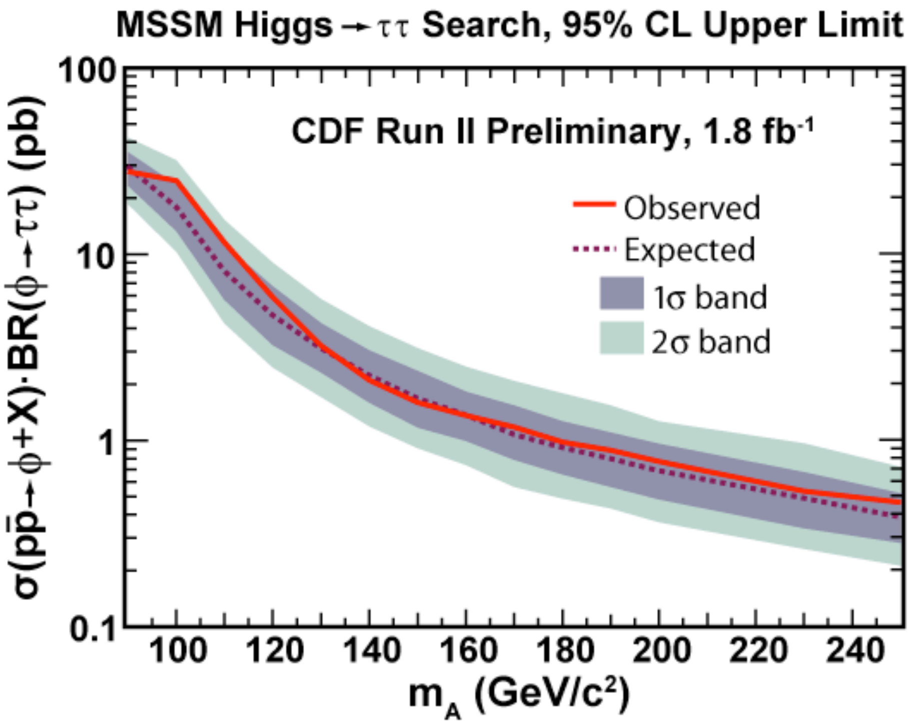


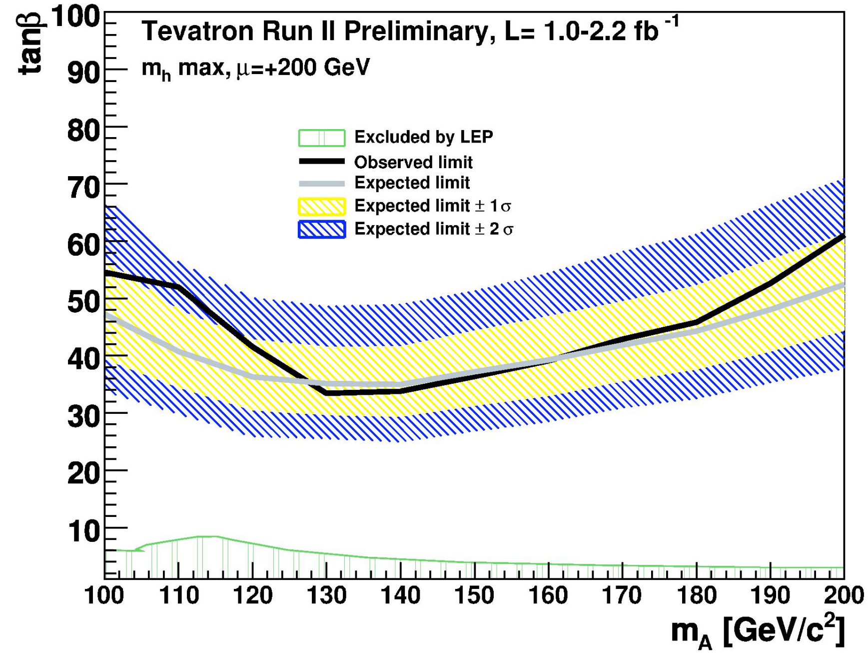
Di-Tau Higgs Boson Search



- Data agree with background prediction

Limits on the MSSM Higgs

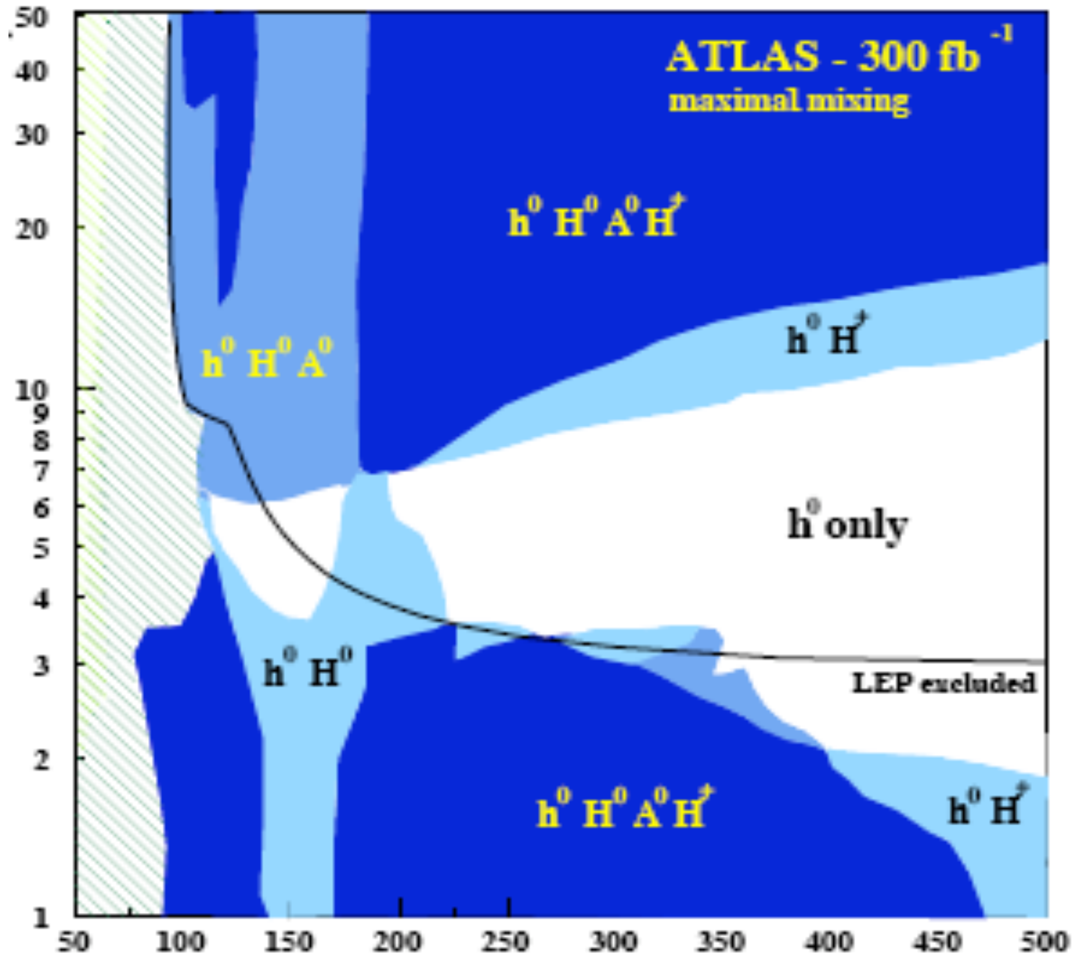




- Data agree with background
  - Use to put an upper limit on the cross section
  - Translate into SUSY parameter space using theoretical cross section prediction
    - E.g. exclude tanβ>35 for m_A=140 GeV/c^2

MSSM Higgs Bosons at LHC

300 fb^{-1}

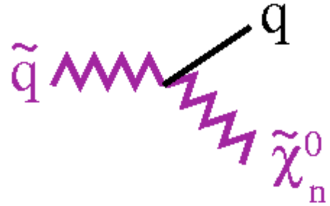


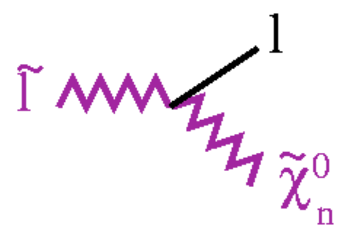
- At least one Higgs boson definitely observable
- Often only one Higgs boson observable

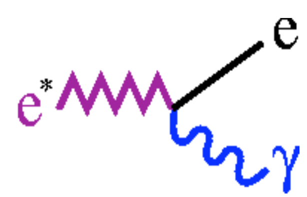
Physics Beyond the Standard Model

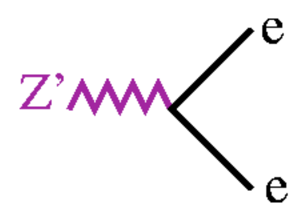
The Unknown beyond the Standard Model

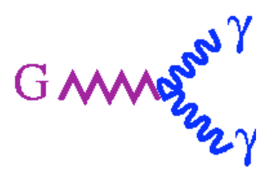
- Many good reasons to believe there is as yet unknown physics beyond the SM:
  - Dark matter + energy, matter/anti-matter asymmetry, neutrino masses/mixing +many more (see 1st lecture)
- Many possible new particles/theories:
  - Supersymmetry:
    - Many flavours
  - Extra dimensions (G)
  - New gauge groups (Z', W',…)
  - New fermions (e*, t', b', …)
  - Leptoquarks
- Can show up!
  - As subtle deviations in precision measurements
  - In direct searches for new particles

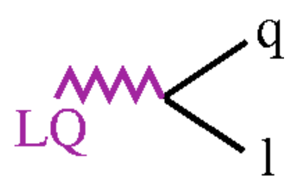


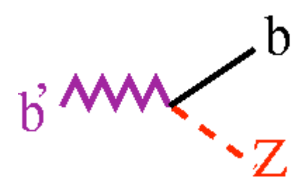




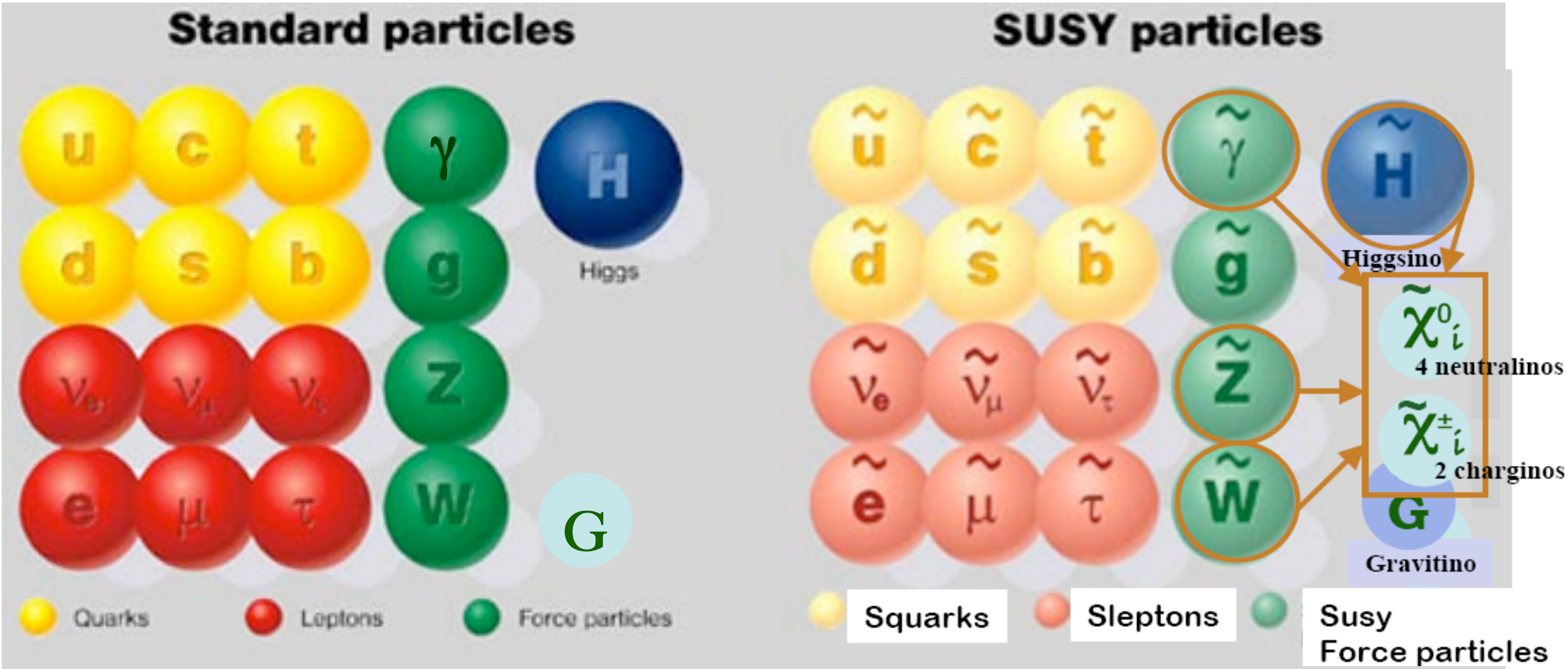








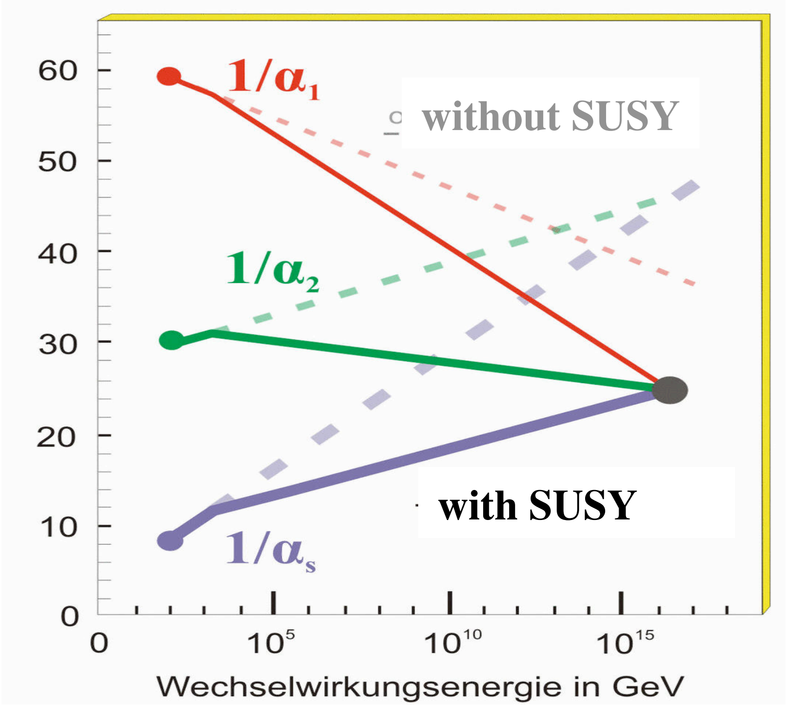
Supersymmetry (SUSY)

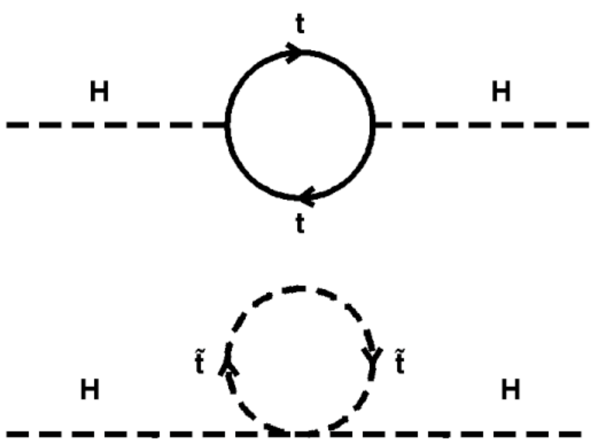


- SM particles have supersymmetric partners:
  - Differ by 1/2 unit in spin
    - **Sfermions** (squark, selectron, smuon, ...): spin 0
    - **gauginos** (chargino, neutralino, gluino,…): spin 1/2
- No SUSY particles found as yet:
  - SUSY must be broken: breaking mechanism determines phenomenology
  - More than 100 parameters even in “minimal” models!

What's Nice about SUSY?

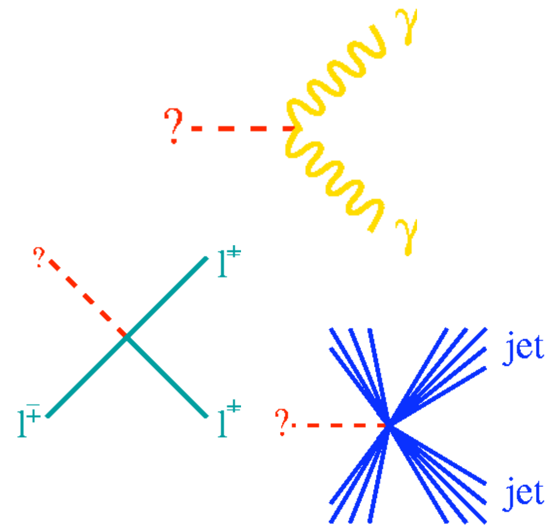
- Introduces symmetry between bosons and fermions
- Unifications of forces possible
  - SUSY changes runnning of couplings
- Dark matter candidate exists:
  - The lightest neutral gaugino
  - Consistent with cosmology data
- No fine-tuning required
  - Radiative corrections to Higgs acquire SUSY corrections
    - Cancellation of fermion and sfermion loops
- Also consistent with precision measurements of M_W and M_{top}
  - But may change relationship between M_W, M_{top} and M_H





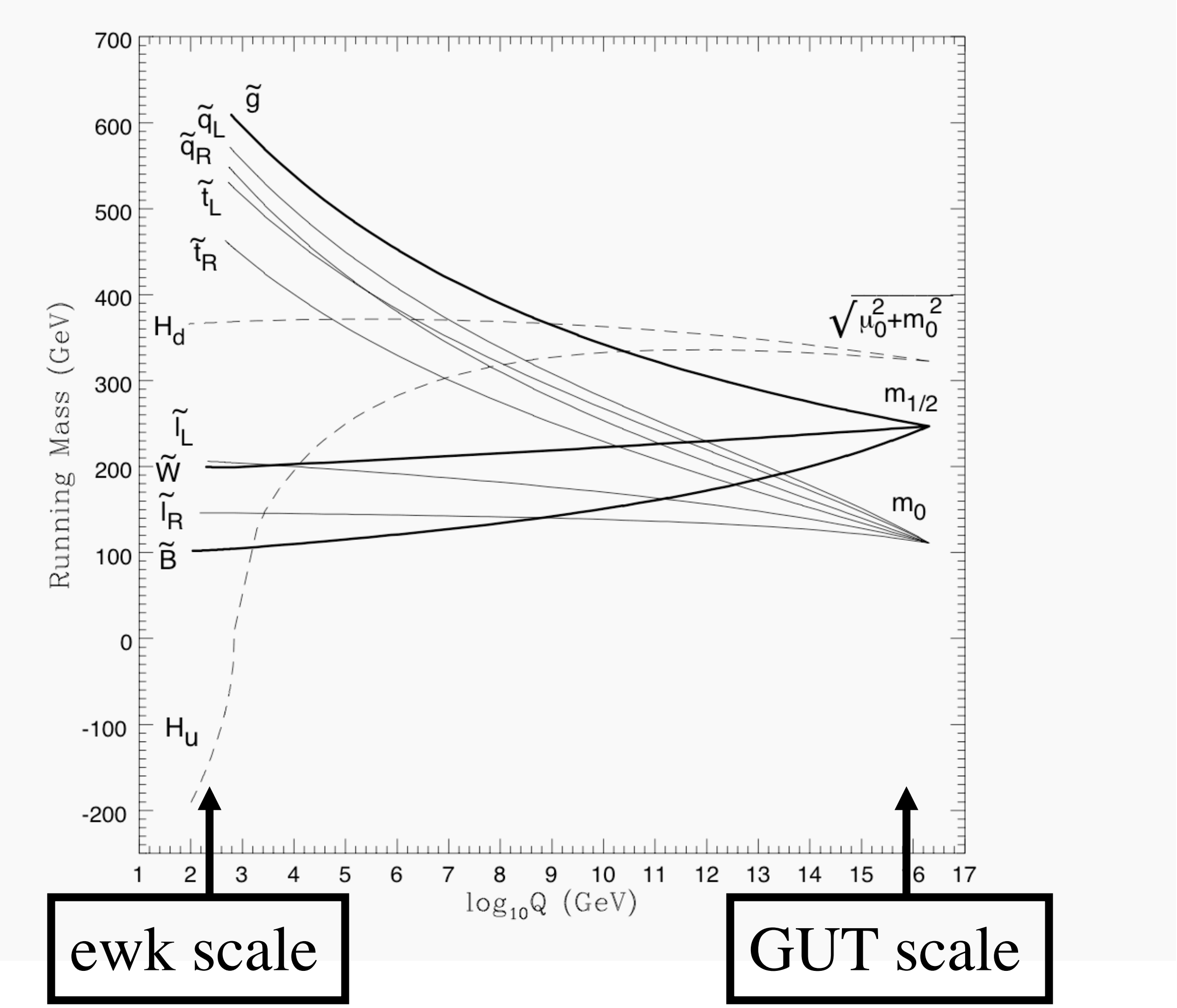
SUSY Comes in Many Flavors

- Breaking mechanism determines phenomenology and search strategy at colliders
  - GMSB:
    - Gravitino is the LSP
    - Photon final states likely
  - mSUGRA
    - Neutralino is the LSP
    - Many different final states
    - Common scalar and gaugino masses
  - AMSB
  - Split-SUSY: sfermions very heavy



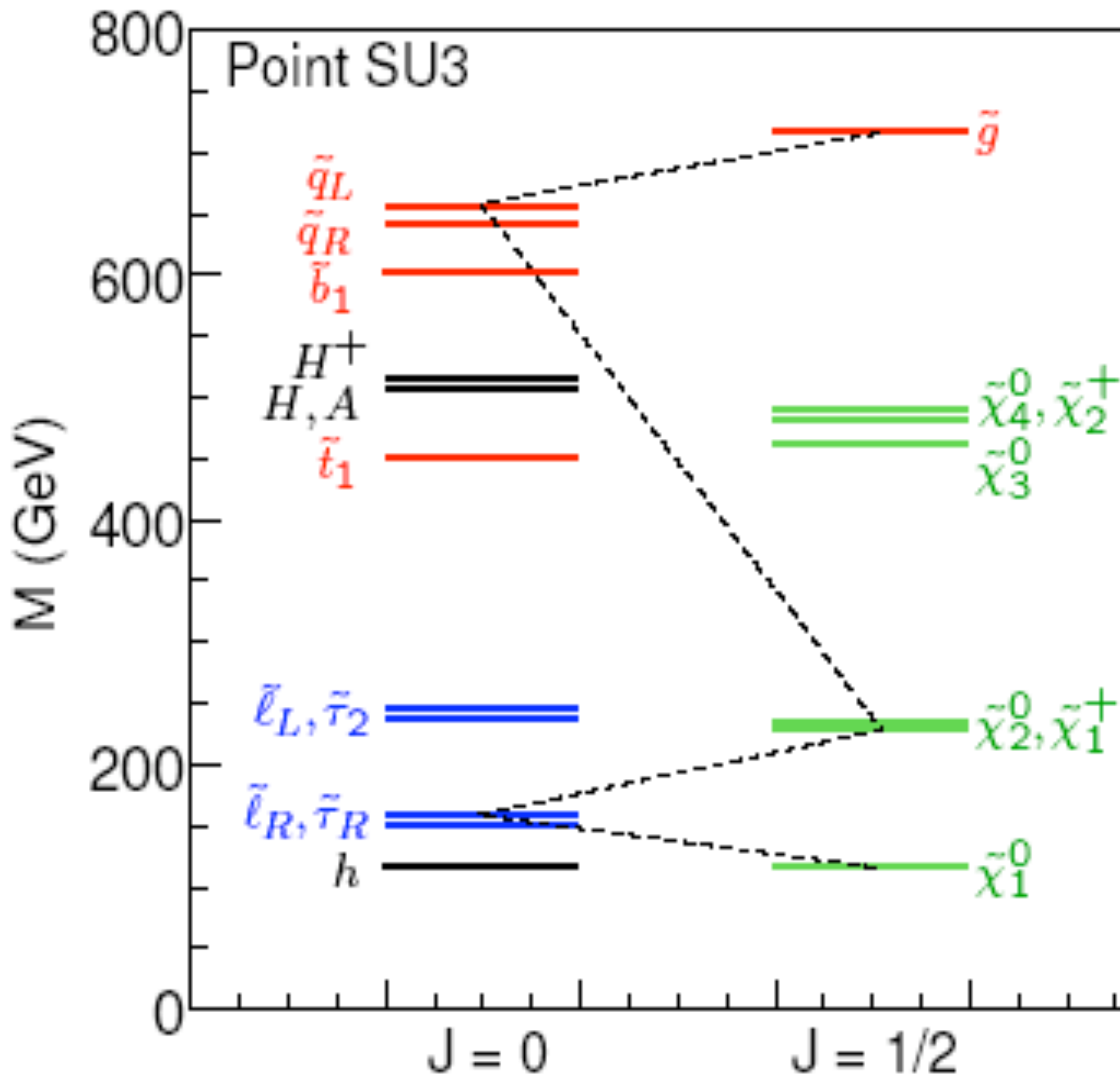
- R-parity
  - Conserved: Sparticles produced in pairs
    - Yields natural dark matter candidate
  - Not conserved: Sparticles can be produced singly
    - constrained by proton decay if violation in quark sector
    - Could explain neutrino oscillations if violation in lepton sector

Mass Unification in mSUGRA

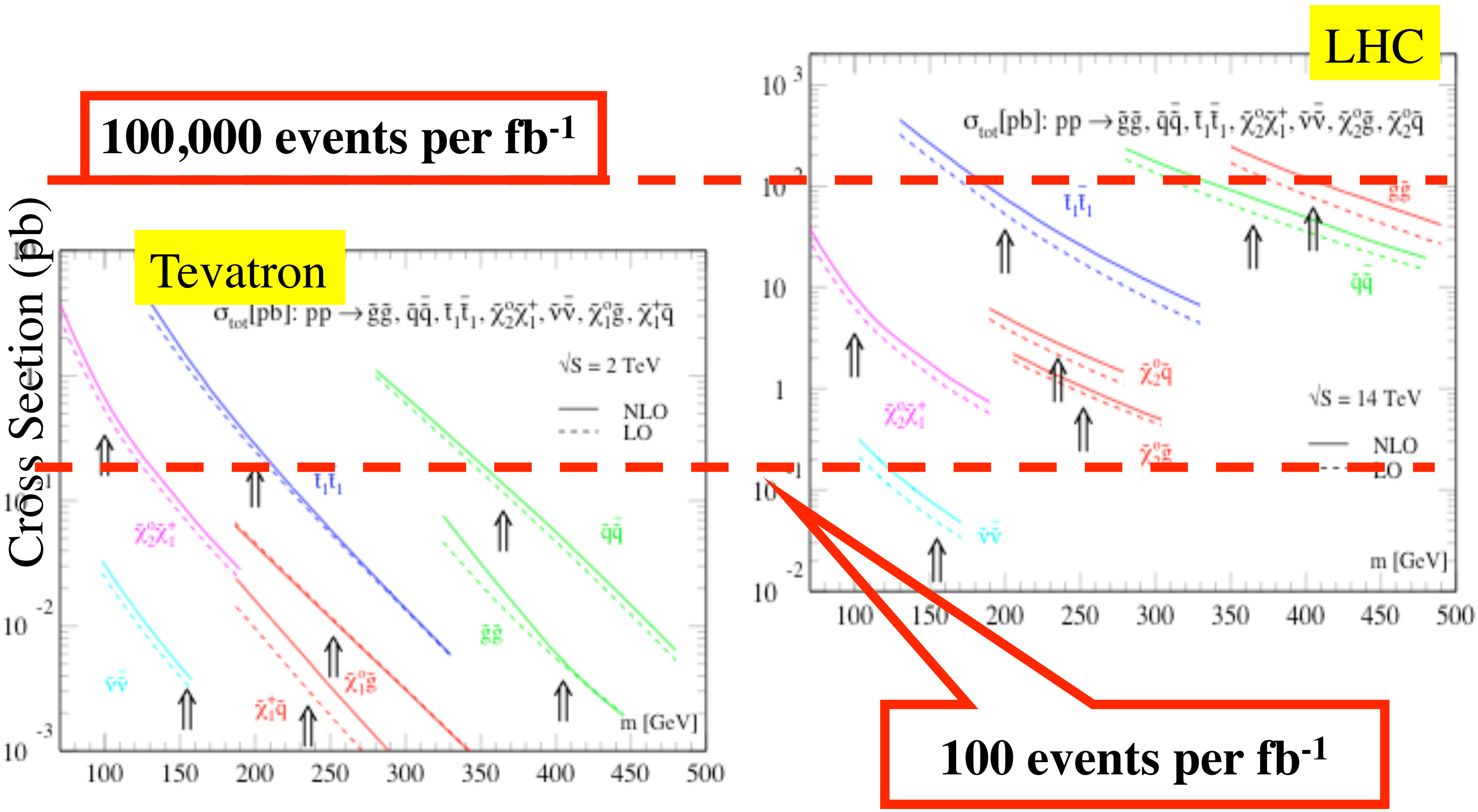


- Common masses at GUT scale: m_0 and $m_{1/2}$
  - Evolved via renormalization group equations to lower scales
  - Weakly coupling particles (sleptons, charginos, neutralions) are lightest

A Typical Sparticle Mass Spectrum

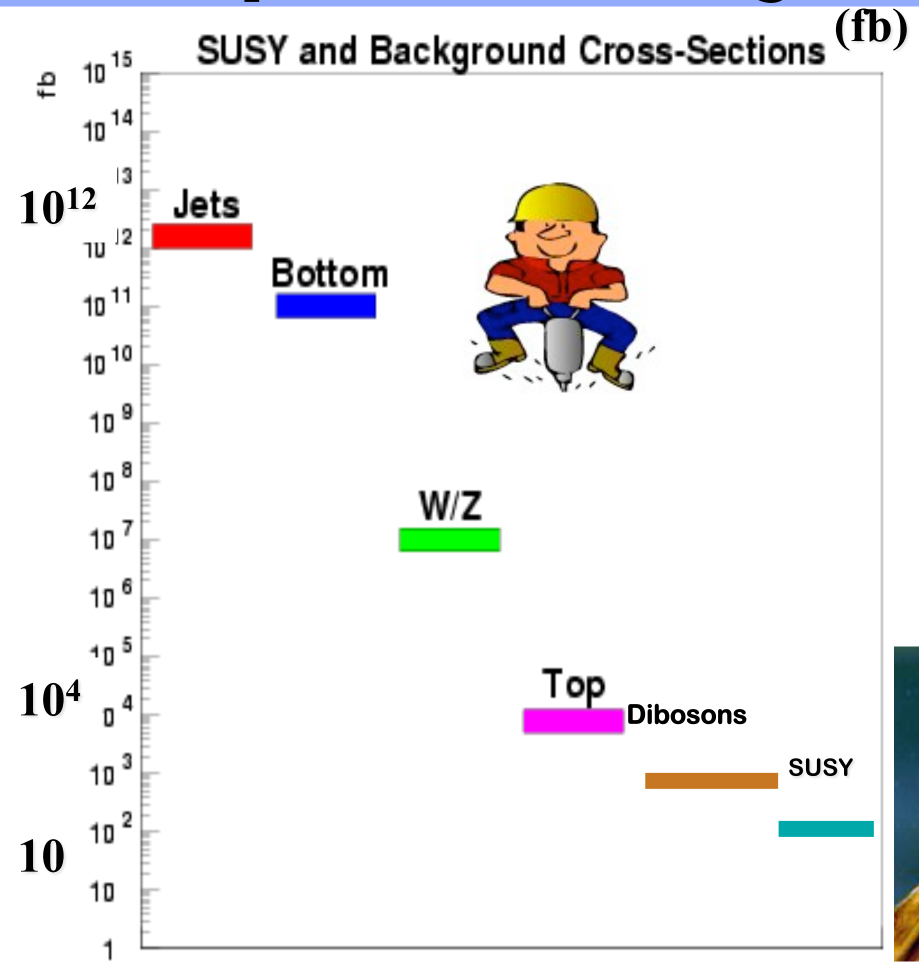


Sparticle Cross Sections



T. Plehn, PROSPINO

SUSY compared to Background



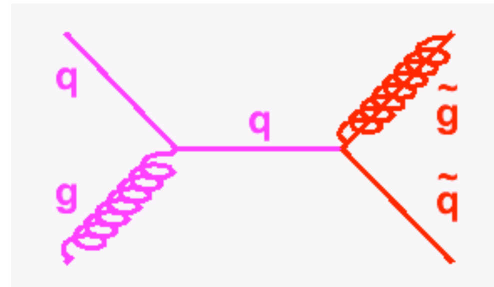
- Cross sections rather low
  - Else would have seen it already!
- Need to suppress background efficiently

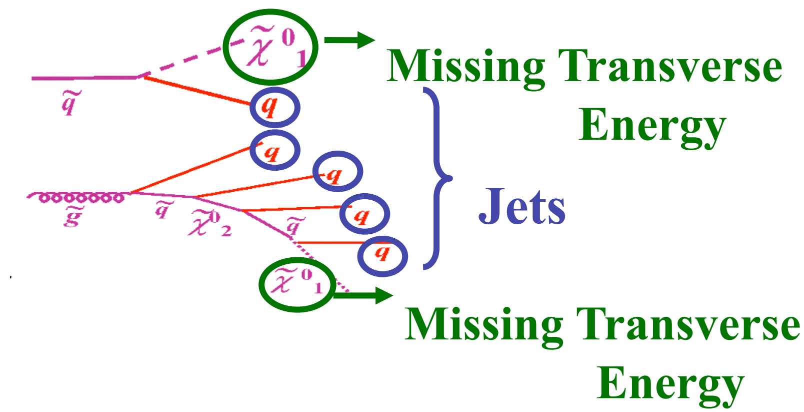
Strategy for SUSY Searches

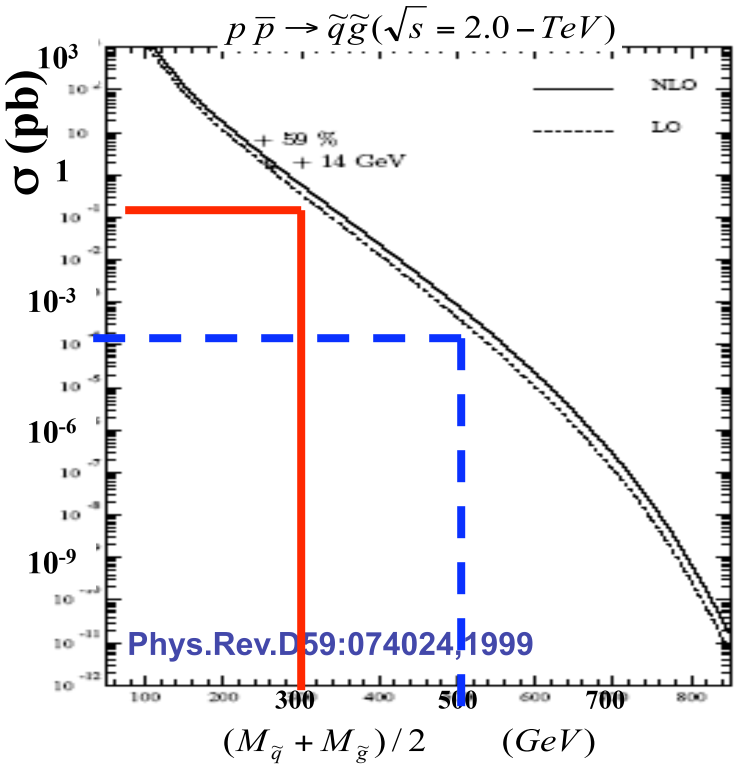
- *Minimal Supersymmetric Standard Model* (MSSM) has more than 100 parameters
  - Impossible to scan full parameter space
  - Many constraints already from
    - Precision electroweak data
    - Lepton flavour violation
    - Baryon number violation
    - …
- Makes no sense to choose random set
  - Use simplified well motivated "benchmark" models
    - Ease comparison between experiments
- Try to make interpretation model independent
  - E.g. not as function of GUT scale SUSY particle masses but versus EWK scale SUSY particle masses
  - Limits can be useful for other models

Generic Squarks and Gluinos

- Squark and Gluino production:
  - Signature: jets and $\not{E}_T$







Strong interaction => large production cross section

for M(g) ≈ 300 GeV/c^2:

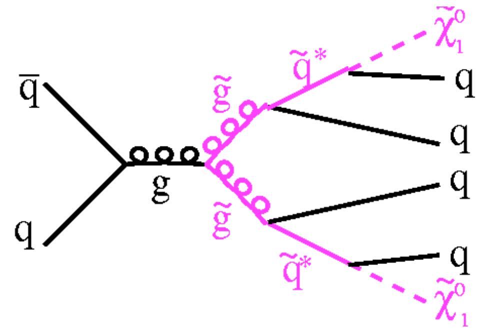
1000 event produced/ fb^{-1}

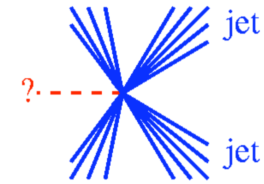
for M(g) ≈ 500 GeV/c^2:

1 event produced/ fb^{-1}

Signature depends on $\tilde{q}$ and $\tilde{g}$ Masses

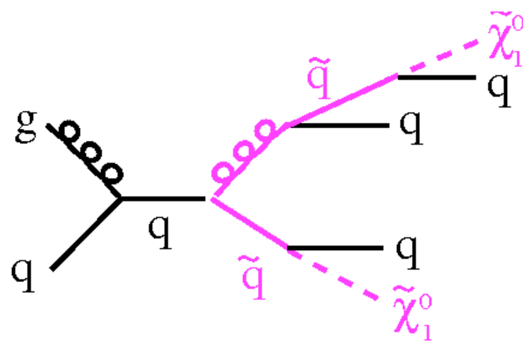
- Consider 3 cases:
  1. $m(\tilde{g})<m(\tilde{q})$

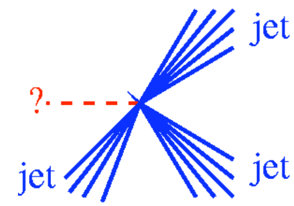




4 jets + E_T^{miss}

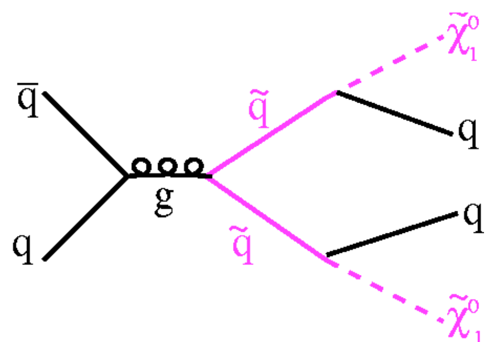
  2. $m(\tilde{g})\approx m(\tilde{q})$

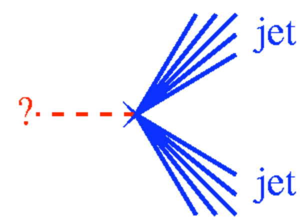




3 jets + E_T^{miss}

  3. $m(\tilde{g})>m(\tilde{q})$





2 jets + E_T^{miss}

$\boxed{\text{Optimize for different signatures in different scenarios}}$

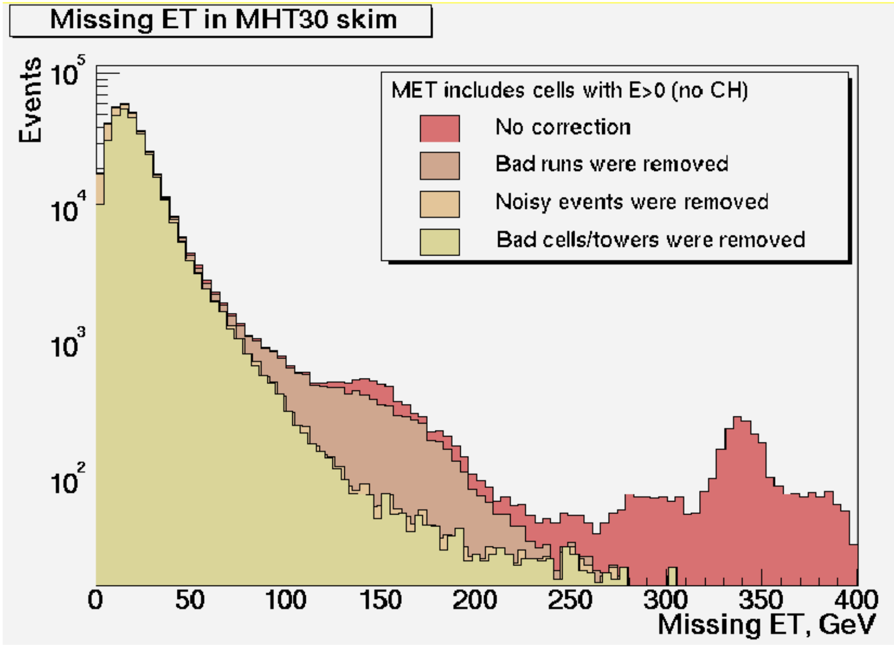
Selection and Procedure

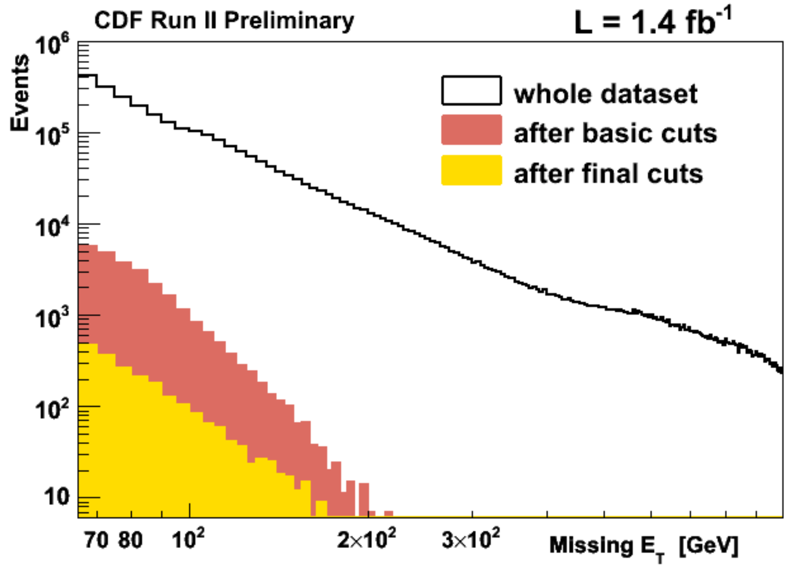
- Selection:
  - Large missing E_T
    - Due to neutralinos
  - Large H_T
    - $H_T=\sum E_T^{jet}$
  - Large $\Delta\phi$
    - Between missing E_T and jets and between jets
    - Suppress QCD dijet background due to jet mismeasurements
  - Veto leptons:
    - Reject W/Z+jets, top

- Procedure:
  1. Define signal cuts based on background and signal MC studies
  2. Select control regions that are sensitive to individual backgrounds
  3. Keep data "blind" in signal region until data in control regions are understood
  4. Open the blind box!

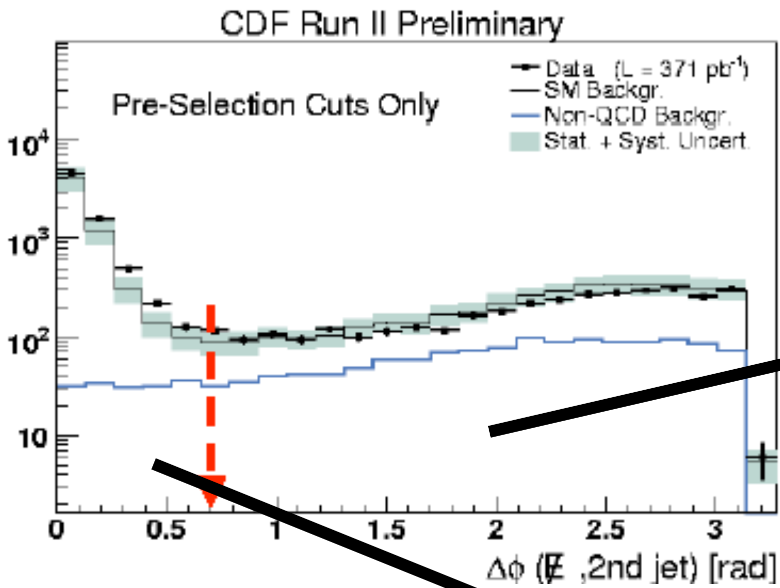
Missing Energy can be caused by Problems

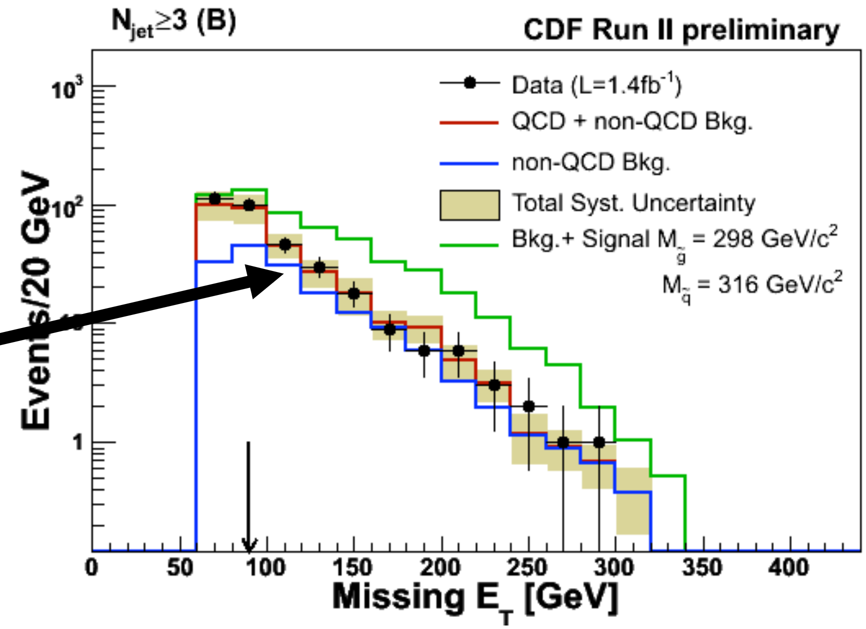
- Data spectrum contaminated by
  - Noise
  - Cosmic muons showering
  - Beam halo muons showering
- Needs “cleaning up”!
  - track matched to jet
  - electromagnetic energy fraction
  - Removal of hot cells
  - Topological cuts against beam-halo



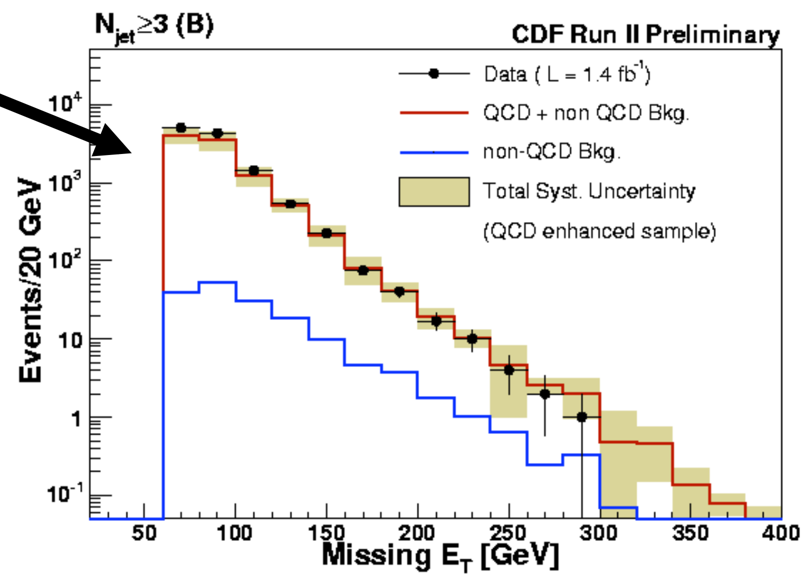


QCD Dijet Rejection Cut



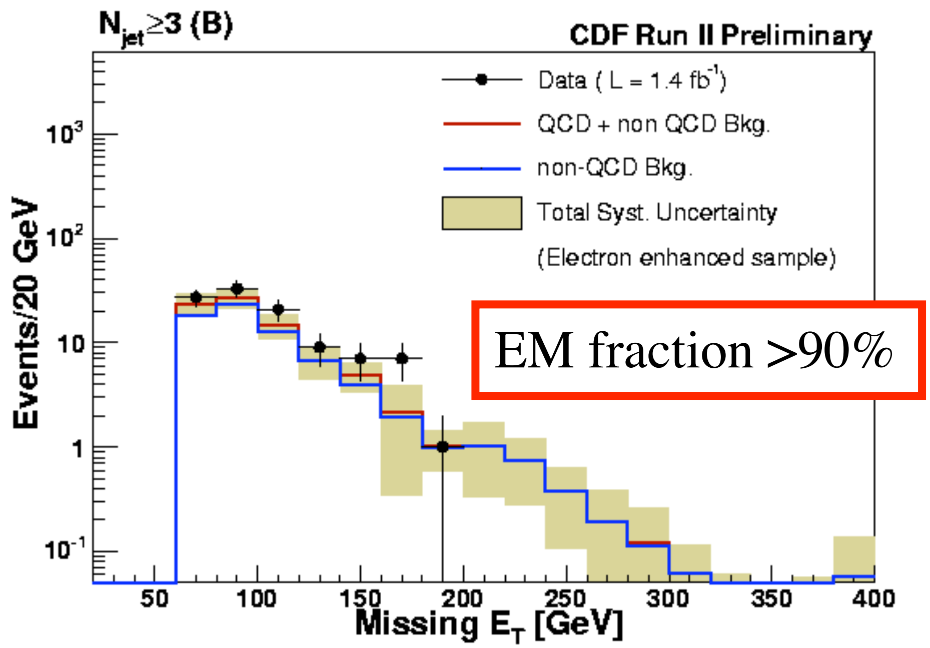


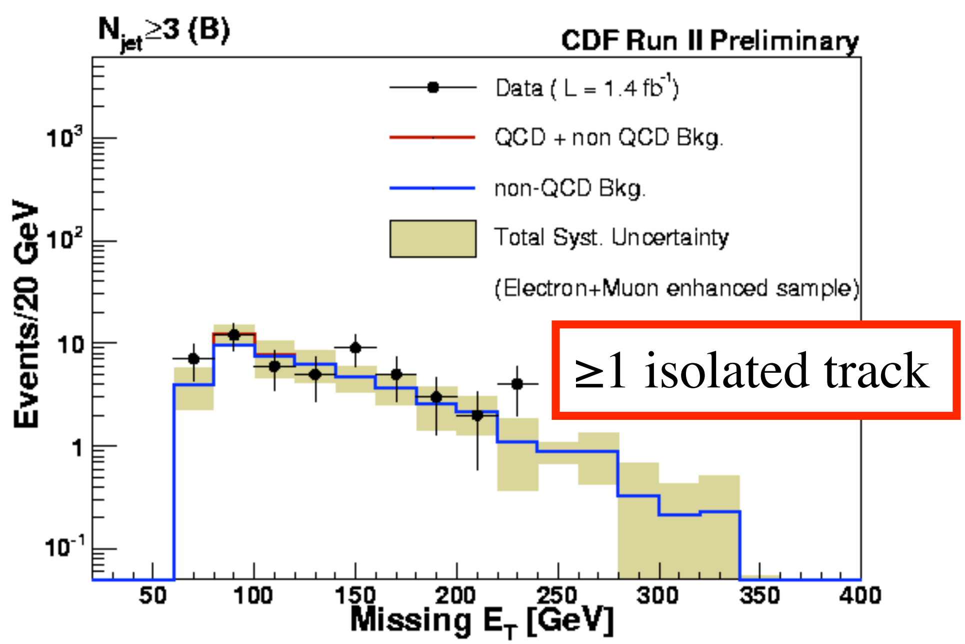
- Cut on $\Delta\phi(\text{jet}, E_T^{miss})$
- Used to suppress and to understand QCD multi-jet background
  - Extreme test of MC simulation



W+jets, Z+jets and Top background

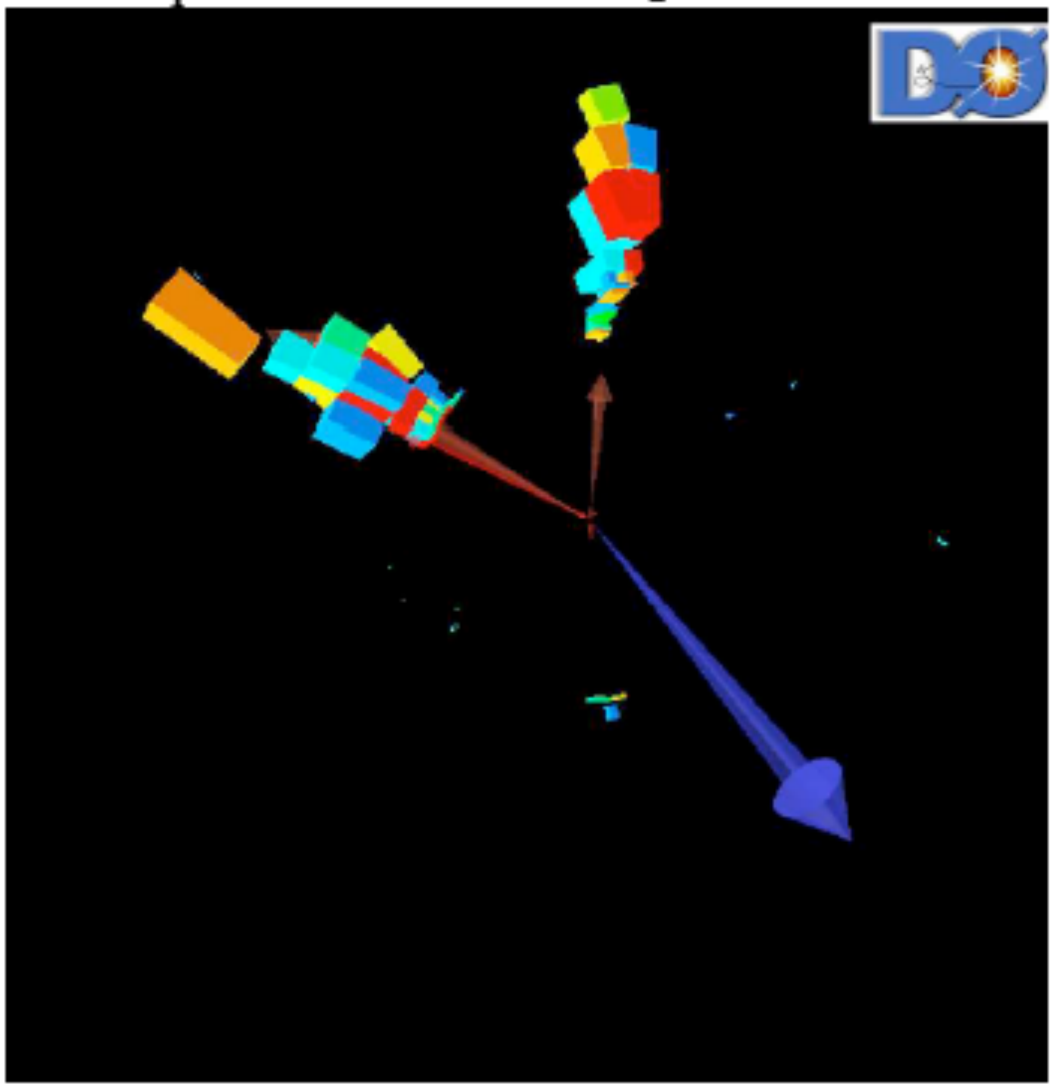
- Background sources:
  - W/Z+jets, top
  - Suppressed by vetoes:
    - Events with jet with EM fraction>90%
      - Rejects electrons
    - Events with isolated track
      - Rejects muons, taus and electrons
- Define control regions:
  - W/Z+jets, top
    - Make all selection cuts but invert lepton vetoes
  - Gives confidence in those background estimates



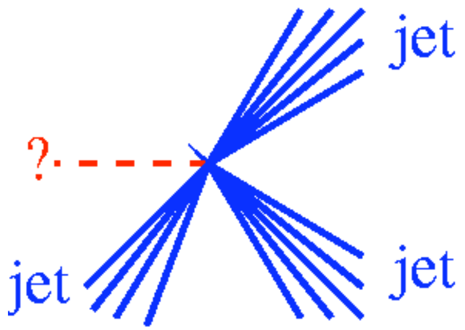


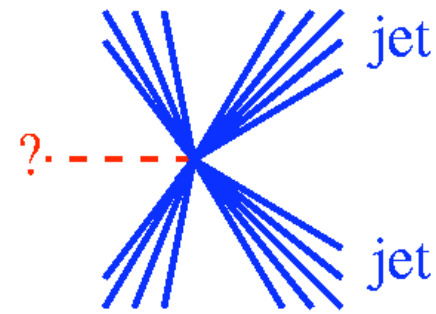
A Nice Candidate Event!

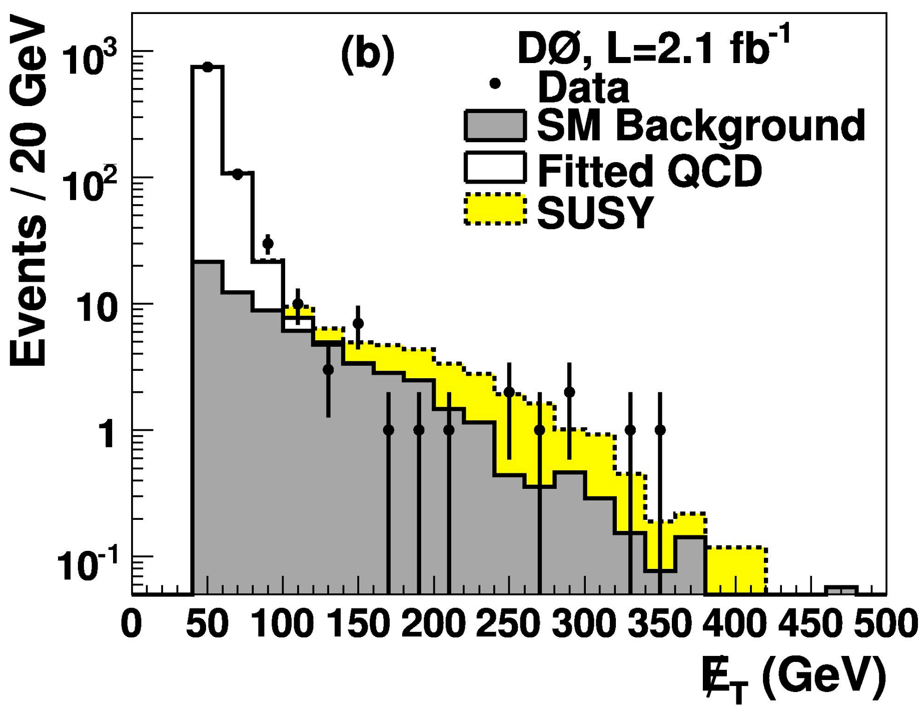
Squark Candidate: $\not\!\!E_T$=381 GeV

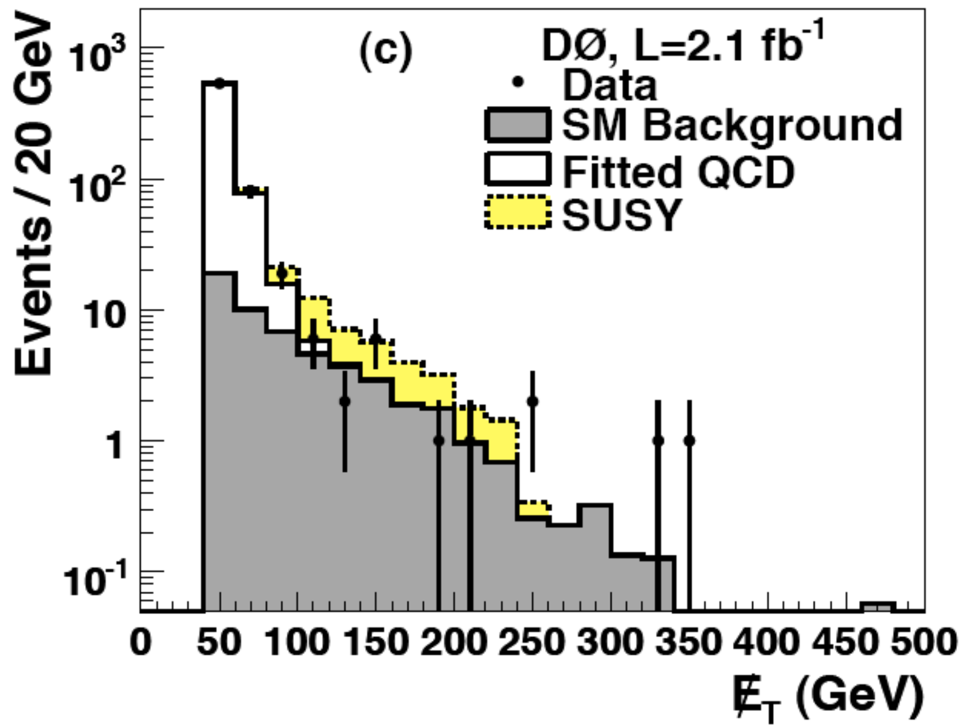


But there is no clear signal…

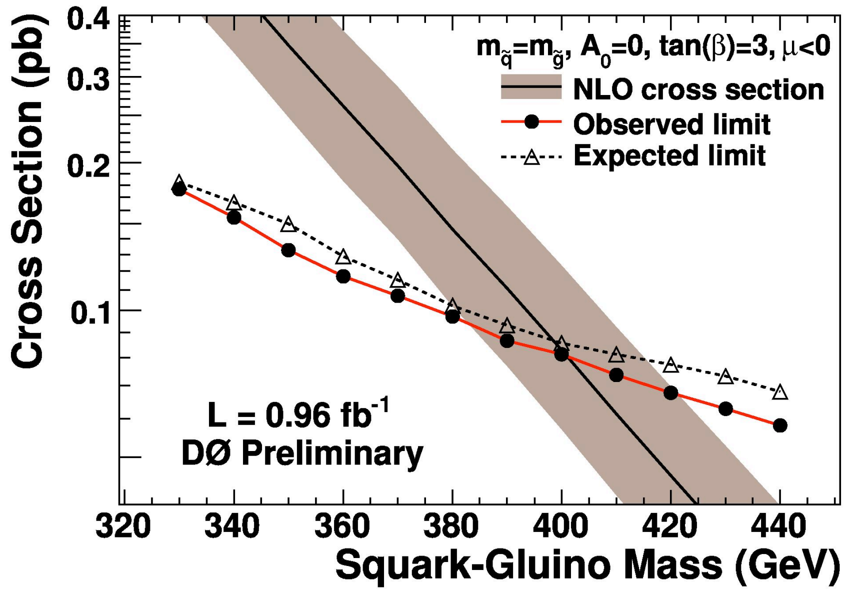


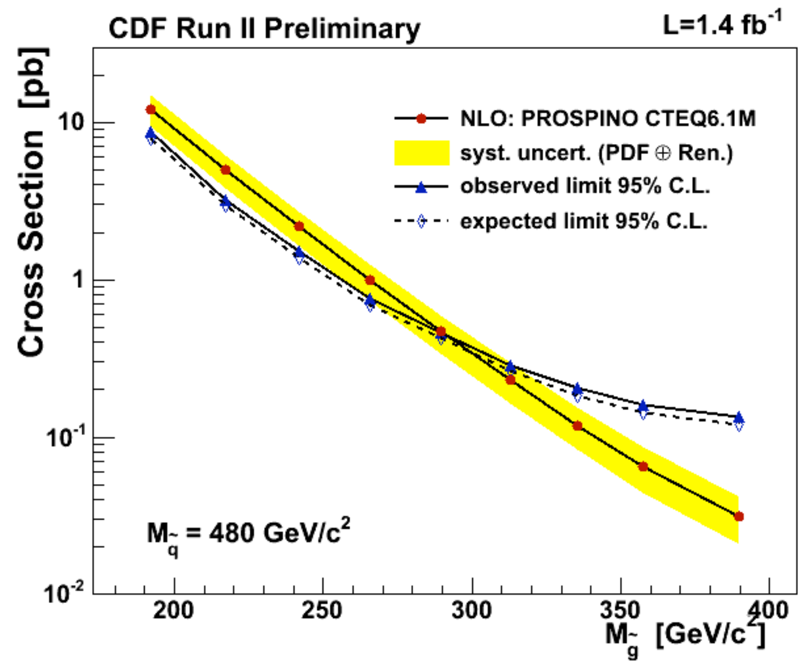






Cross Section Limits

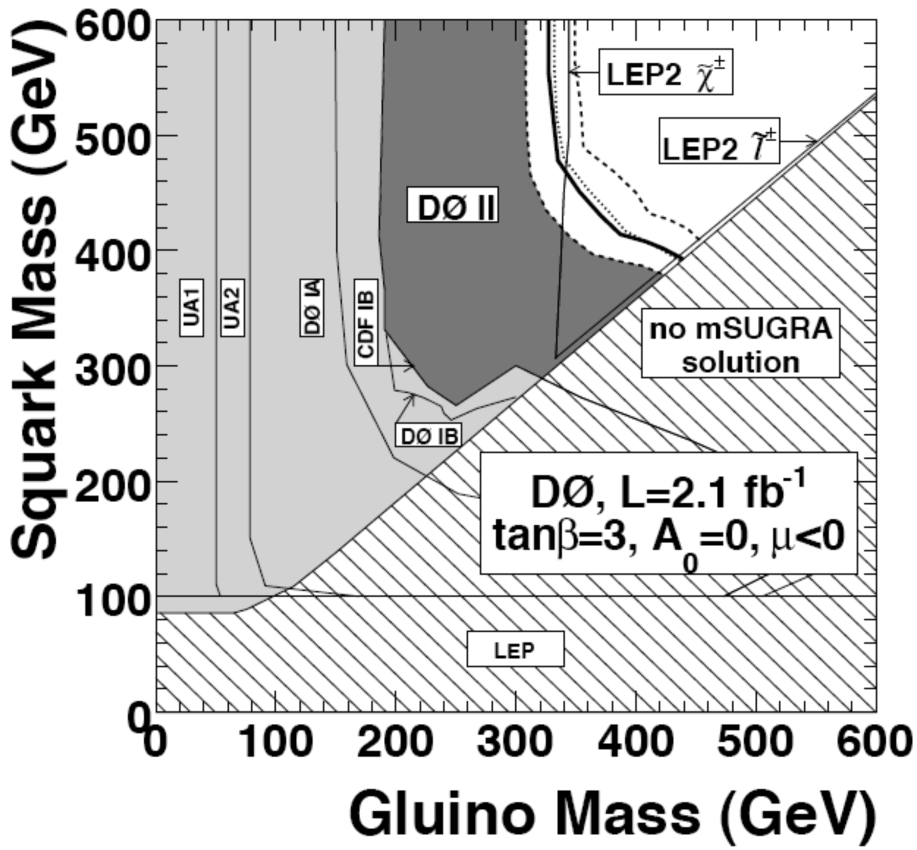




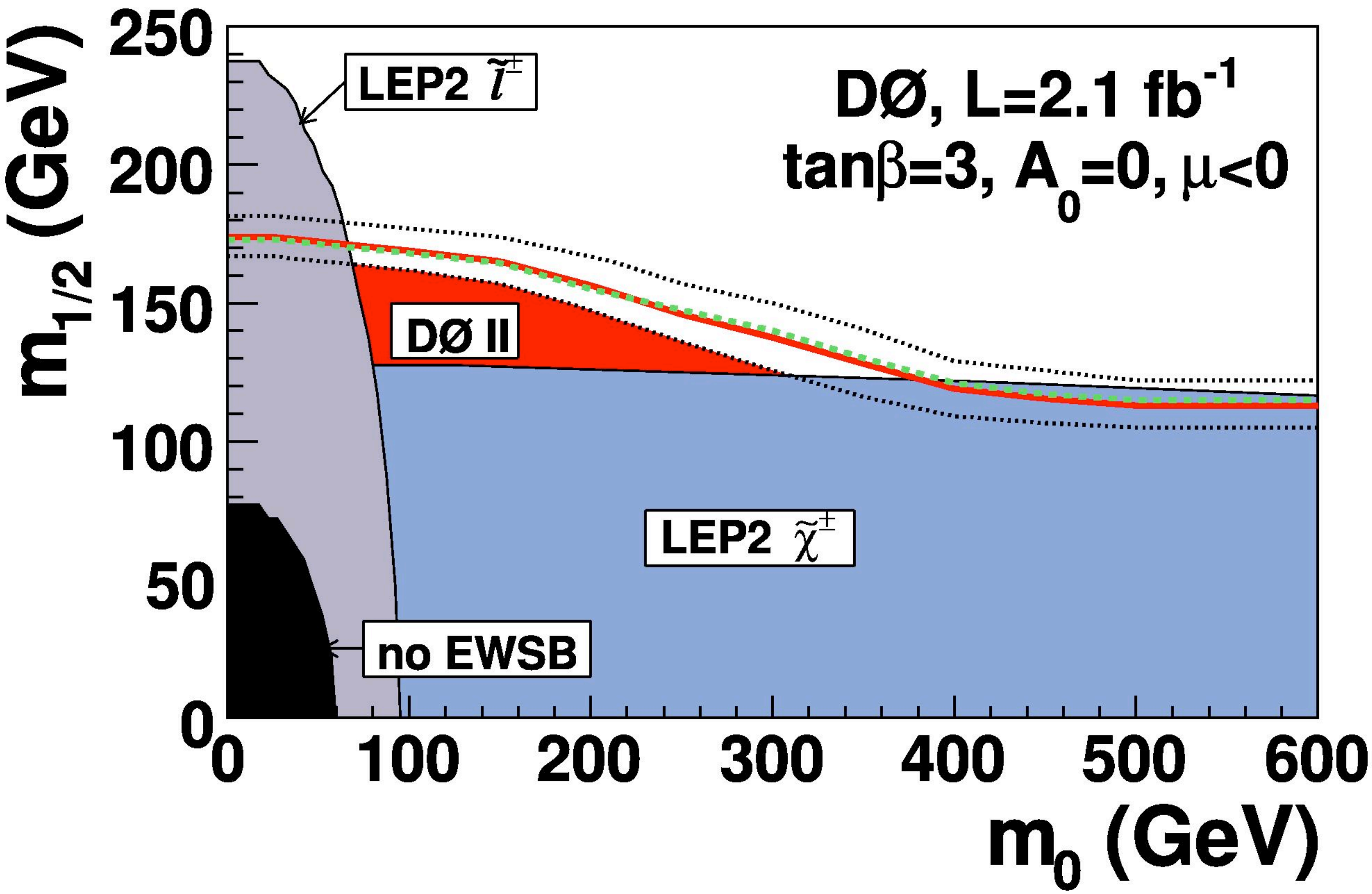
- No excess in data
  - Evaluate upper limit on cross section
  - Find out where it crosses with theory
- Theory has large uncertainty: ~30%
  - Crossing point with theory lower bound ~ represents limit on squark/gluino mass

Squark and Gluino Mass Limits

- Constraints on masses
  - $M(\tilde{g})>308$ GeV
  - $M(\tilde{q})>379$ GeV
- Represented in this plane:
  - Rather small model dependence as long as there is R-parity conservation



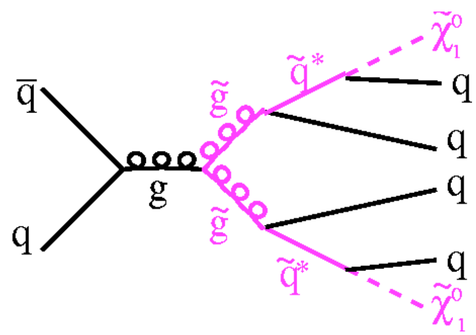
Exclusion of GUT scale parameters

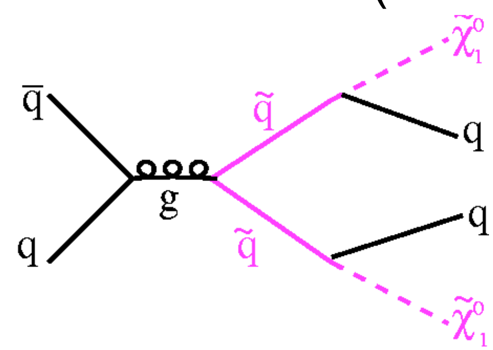


- Nice interplay of hadron colliders and e^+e^- colliders:
  - Similar sensitivity to same high level theory parameters via very different analyses
  - Tevatron is starting to probe beyond LEP in mSUGRA type models

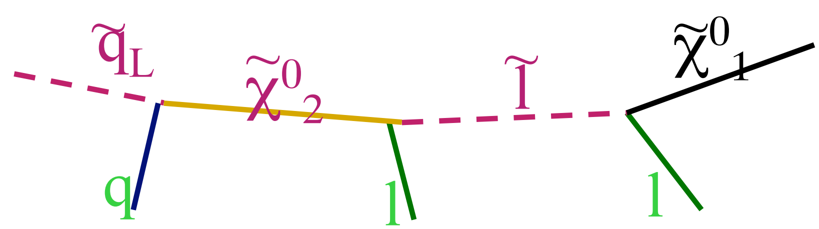
SUSY at the LHC

- Cross section **much** higher, e.g.
  - for $m(\tilde{g})$=400 GeV: $\sigma_{LHC}(\tilde{g}\tilde{g})/\ \sigma_{Tevatron}(\tilde{g}\tilde{g})\approx 20{,}000$
  - for $m(\tilde{q})$=400 GeV: $\sigma_{LHC}(\tilde{g}\tilde{g})/\ \sigma_{Tevatron}(\tilde{g}\tilde{g})\approx 1{,}000$
    - Since there are a lot more gluons at the LHC (lower x)

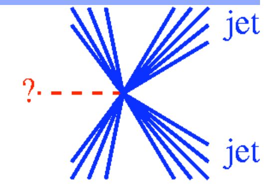




- At higher masses more phase space to decay in cascades
  - Results in additional leptons or jets

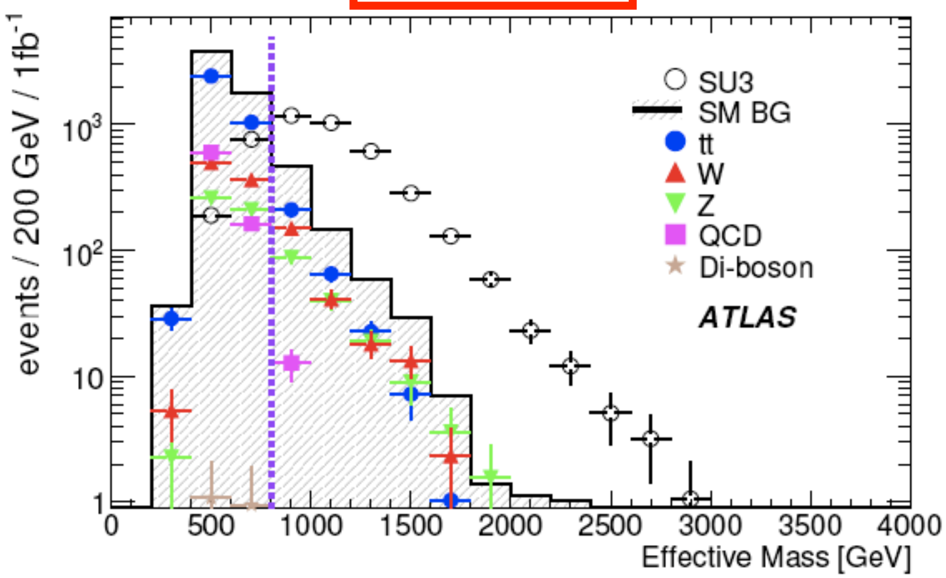


SUSY at the LHC

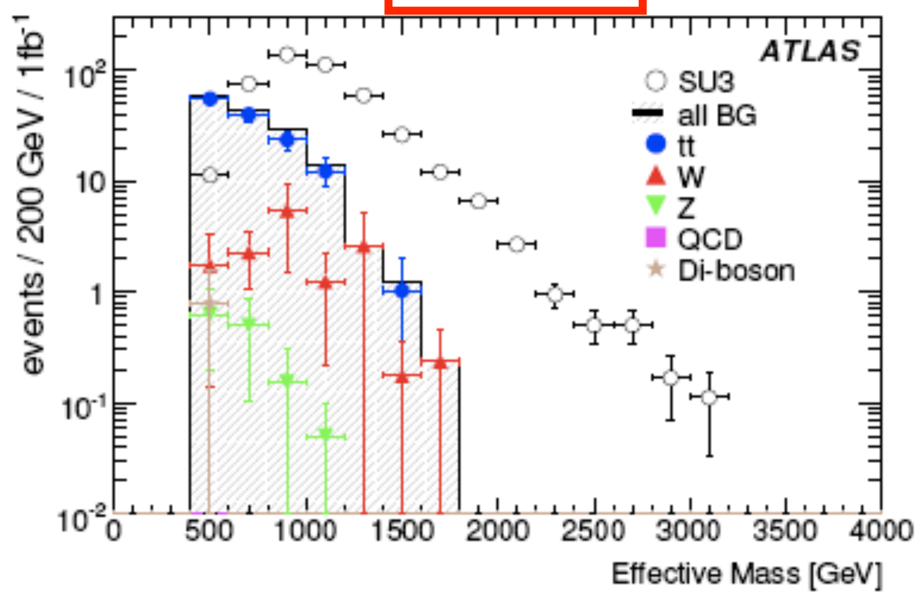


- Example: m($\tilde{q}$)~600 GeV, m($\tilde{g}$)~700 GeV
- Require 4 jets, large missing E_T and 0 or 1 lepton

0 leptons

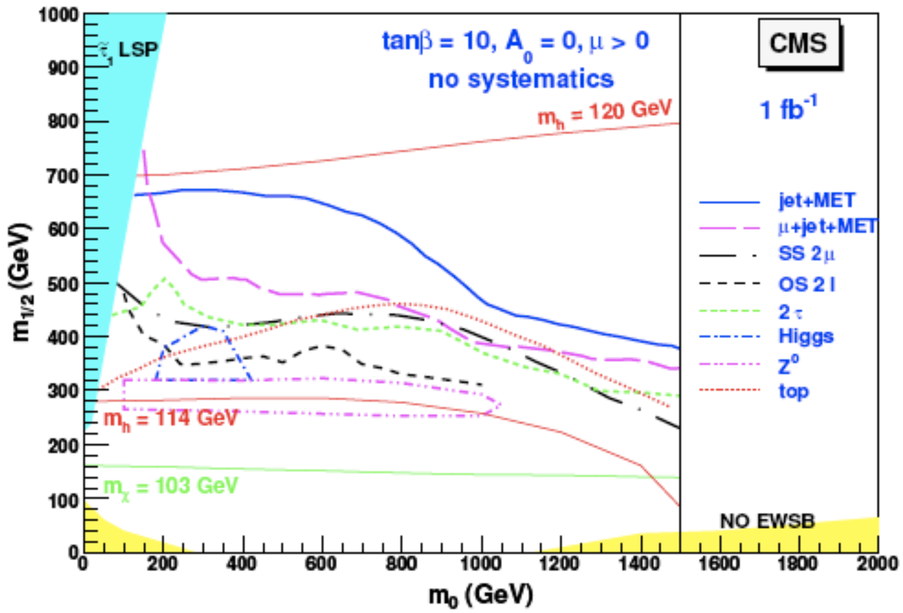


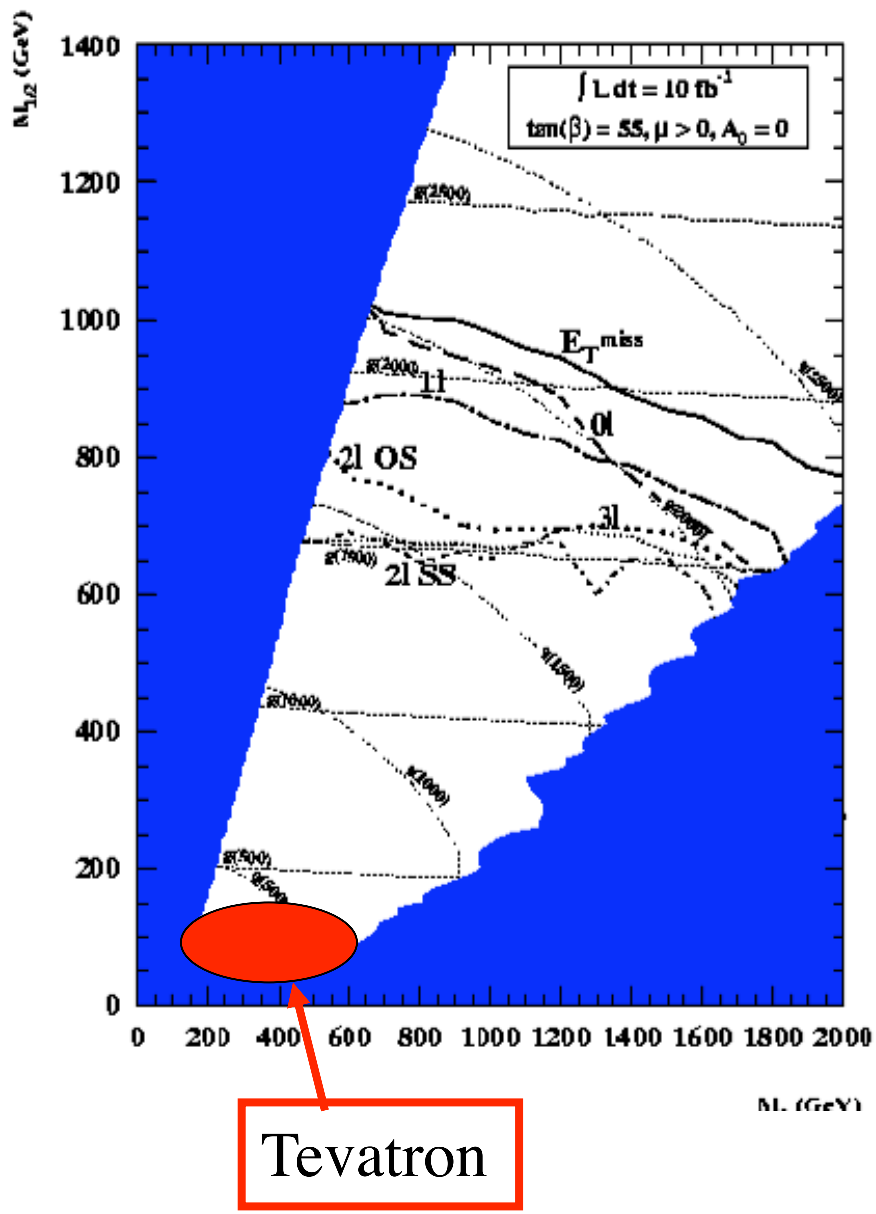
1 lepton



- "Effective Mass" = sum of p_T of all objects
- Similar and great (!) sensitivity in both modes

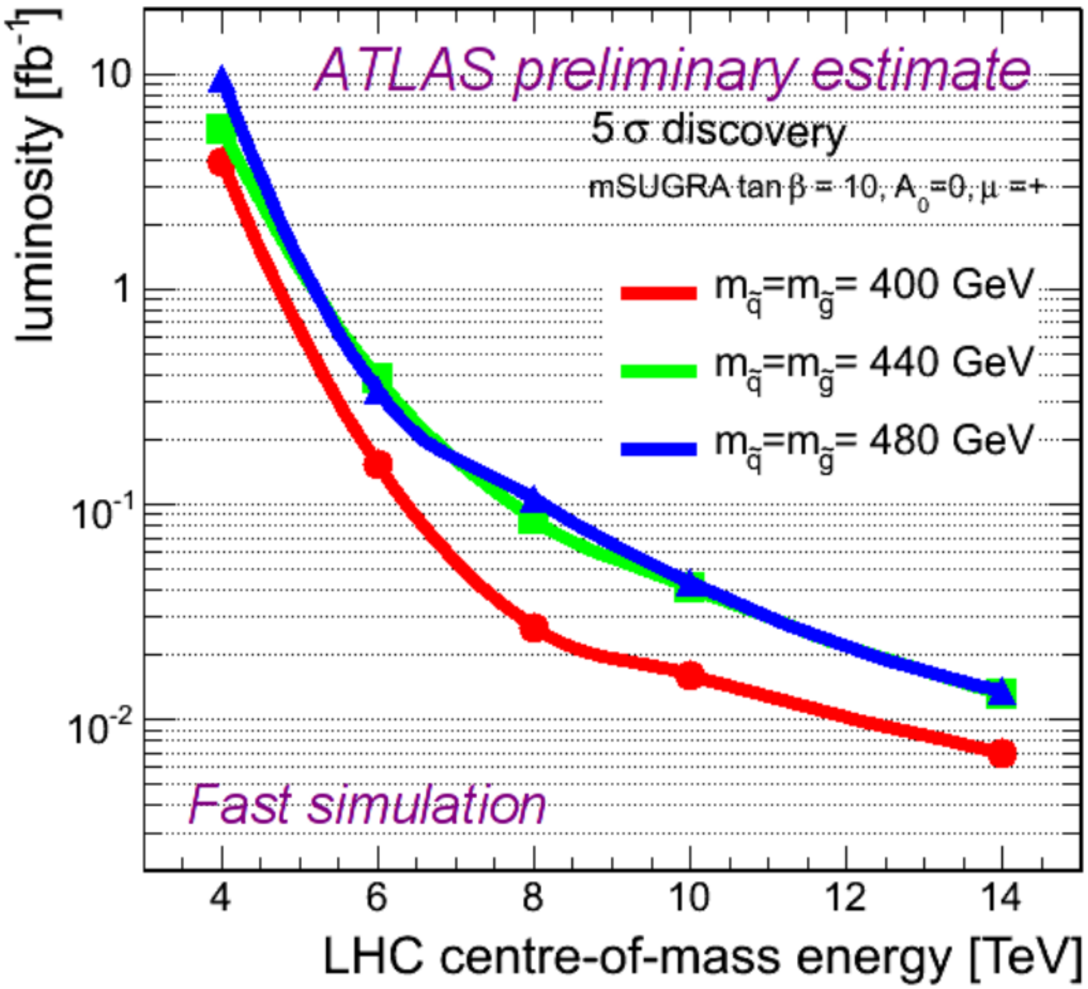
SUSY Discovery Reach





- With 1 fb^{-1}:
  - Sensitive to m($\tilde{g}$)≲1000 GeV/c^2
- With 10 fb^{-1}:
  - Sensitive to m($\tilde{g}$)≲1800 GeV/c^2
- Amazing potential!
  - If data can be understood
  - If current MC predictions are ≈ok

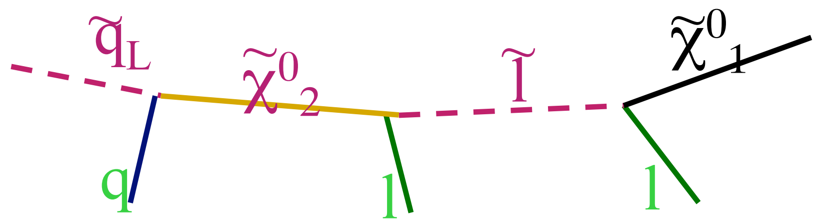
SUSY Searches at 7 TeV

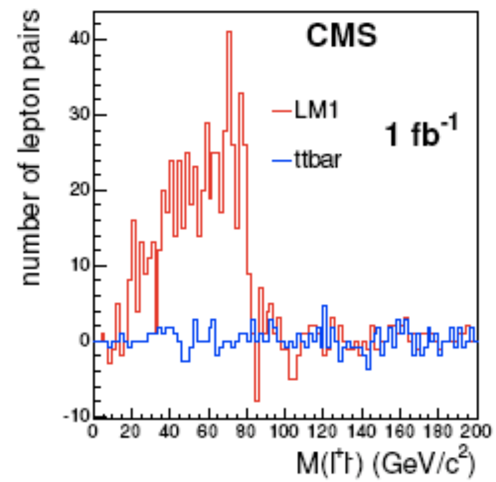


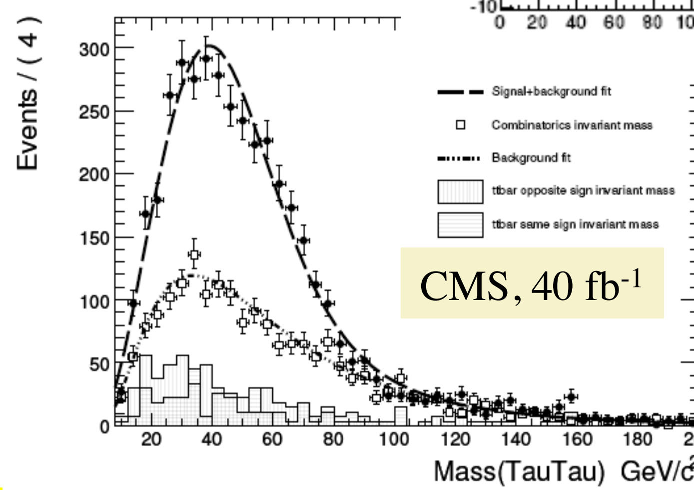
- Requires about 100 pb^{-1} for discovery of 400 GeV gluinos/squarks

What kind of SUSY is it?

- We will need to do SUSY spectroscopy!
  - Rate of 0 vs 1 vs 2 vs n leptons
    - Sensitive to neutralino masses
  - Rate of tau-leptons:
    - Sensitive to $\tan\beta$
  - Kinematic edges
    - obtain mass values
  - Detailed examination of inclusive spectra
  - ….







That would be my dream scenario! It's where the real fun starts!!

Conclusions of Higgs and SUSY

- Direct searches for Higgs boson
  - Tevatron excludes 163-166 GeV based on WW
  - LHC will rival Tevatron at high mass with 1 fb^{-1}
  - Low mass Higgs will need 10 fb^{-1} or more
- Supersymmetry is most promising theory of physics beyond the Standard Model
  - Current limit: $m(\tilde{g})>310$ GeV
    - No signs of it in other searches either
  - LHC will extend beyond Tevatron already with 100 pb^{-1} at 7 TeV (if detectors understood well enough)
- If SUSY is to solve the problems in our theory it will be found at the LHC